Section 22 Vermont

Buffer Strips For Riparian Zone Management

January 1991

US Army Corps
of Engineers
New England Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
January 1991

3. REPORT TYPE AND DATES COVERED
Planning Assistance to States

4. TITLE AND SUBTITLE
Buffer Strips for Riparian Zone Management

5. FUNDING NUMBERS
Section 22
Public Law 93-251

6. AUTHOR(S)
U.S. Army Corps of Engineers
New England Division

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers, New England Division
424 Trapelo Road
Waltham, MA 02254-9149

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers, New England Division
424 Trapelo Road
Waltham, MA 02254-9149

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
This study was requested by the Vermont Department of Environmental Conservation

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release
Distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This study provides a review of technical literature concerning the width of riparian buffer strips needed to protect water quality and maintain other important values provided by riparian ecosystems.

Under most circumstances (20 to 30 meter wide) buffers appear adequate to remove suspended sediments from surface flows. Narrow buffers may also reduce nitrogen levels in surface runoff and groundwater. There appears to be insufficient information available in the literature to formulate a matrix which completely relates appropriate buffer strip width to stream characteristics, upland land use, and riparian functions.

14. SUBJECT TERMS
Riparian Buffer Strips, water quality, suspended sediments, nitrogen, surface runoff, wetlands

15. NUMBER OF PAGES
60

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

BUFFER STRIPS FOR RIPARIAN ZONE MANAGEMENT

(A Literature Review)

prepared for

State of Vermont

by

DEPARTMENT OF THE ARMY
NEW ENGLAND DIVISION, CORPS OF ENGINEERS
WALTHAM, MASSACHUSETTS

January 1991

EXECUTIVE SUMMARY

This study provides a review of technical literature concerning the width of riparian buffer strips needed to protect water quality and maintain other important values provided by riparian ecosystems. This literature review was conducted at the request of the Vermont Department of Environmental Conservation.

The available technical literature suggests that fairly narrow buffer strips (i.e < 30 m) can adequately provide many riparian functions. Shade provided by trees in narrow (10-20 m wide) buffers generally appears adequate to control the temperature of small streams. Under most circumstances 20 to 30 m wide buffers appear adequate to remove suspended sediments from surface flows, unless the surface drainage within the buffer is channelized. Narrow (20 m) buffers may also significantly reduce nitrogen levels in surface runoff and groundwater. Although riparian ecosystems and other wetlands can act as phosphorus sinks, there is insufficient information available to evaluate the long-term ability of riparian buffer strips to retain phosphorus. Relatively wide buffers are probably required to provide sufficient habitat for riparian wildlife and plants, and to serve as travel corridors for riparian and upland species.

Although fixed buffer widths are sometimes suggested in the literature, appropriate buffer widths vary on a case by case basis with site topography, existing riparian zone development, water quality protection goals, and regional planning objectives. Several recently developed approaches for determining buffer strip width on a case by case basis are presented.

There appears to be insufficient information available in the literature to formulate a matrix which completely relates appropriate buffer strip width to stream characteristics, upland land use, and riparian functions. Although this approach might be useful from a regulatory standpoint, most values in the matrix would heavily reflect professional judgment, rather than sound data provided in the literature.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

STUDY AUTHORITY

This study was conducted by the New England Division of the U.S. Army Corps of Engineers at the request of the Vermont Department of Environmental Conservation. Authority for the study is contained in Section 22 of Public Law 93-251, as amended ("Planning Assistance to States"). The Section 22 program authorizes the Corps to assist the states in preparation of plans for the development, utilization, and conservation of water resources.

STUDY PURPOSE AND SCOPE

This study provides a review of technical literature concerning the width of riparian buffer strips needed to protect water quality and maintain other important values provided by riparian ecosystems. The study was requested by the Vermont D.E.C to aid the agency in formulating technically sound guidelines for buffer strip width. In particular, the D.E.C. expressed an interest in developing a "matrix" which relates needed buffer strip width to stream characteristics, upland land use, and riparian functions. This literature review was conducted, in part, to determine if sufficient technical data were available to develop such a matrix. The report also describes several other approaches developed to determine buffer strip width, and provides an extensive bibliography concerning riparian buffer strips and related literature.

RIPARIAN BUFFER STRIPS

Riparian ecosystems are transitional zones (ecotones) situated between aquatic and upland ecosystems (Mitsch and Gosselink, 1986). Although characteristics of these ecosystems vary widely (Brinson et al., 1981), those along rivers and streams are often fairly narrow and vulnerable to disruption by development. It is generally accepted that undeveloped riparian habitat should be left along streams and rivers to protect water quality and maintain other important riparian functions (see Table 1). These areas are generally referred to as "buffer strips". Other commonly used related terms include buffer zones, streamside management zones, greenways, and filter strips.

Although the importance of riparian buffer strips is well accepted, there is less agreement as to how wide buffers must be in order to function effectively. In part, disagreement stems from the variable nature of riparian zones and associated aquatic ecosystems. Furthermore, buffer width required varies with the functional value of the riparian ecosystem one wishes to protect. Finally, economic interests are frequently at odds with environmental concerns during the formulation of riparian zone management policies.

TABLE 1: Functional Vales of Riparian Buffer Strips

Water Quality Protection

Temperature

Shade and cover provided by riparian vegetation can moderate water temperature in small (low order) streams.

Sediments and Other Contaminants

Buffer strips filter sediments and other contaminants (e.g. pesticides, heavy metals) from surface flow. Buffer strips also prevent erosion in riparian areas and preclude development which could lead to increased contaminant loading.

Nutrients (Nitrogen and Phosphorus)

Buffer strips reduce nutrient inputs into streams by: 1) filtering sediment bound nutrients from surface flow, 2) removing nutrients from groundwater via uptake in vegetation and by denitrification, and 3) precluding development which could increase nutrient loading (i.e. septic systems).

Maintenance of Streamflow

Buffer strips can store water and help maintain stream base flow (and water quality) during low flow periods.

Streambank and Streambed Stability

Streambank Erosion

Roots of streamside vegetation can stabilize streambanks and reduce streambank erosion.

Streambed Erosion

Buffer strips can reduce runoff and streambed scour caused by excessive flows.

TABLE 1: continued

Enhancement of Fish and Wildlife Resources

Habitat for Wildlife and Vegetation

Buffer strips can provide productive habitat for numerous plants and animals. Riparian buffers can also provide "corridors" which facilitate movement of wildlife between habitat "islands" in otherwise developed areas.

Protection of Habitat for Fish and Other Aquatic Life

Riparian buffers can moderate stream temperature, and improve water quality by reducing loading of sediments, contaminents, and nutrients. Snags derived from riparian areas provide important habitat for fish and aquatic invertebrates. Riparian buffers can minimize disruption of aquatic communities by maintaining streamflow during low flow periods and by minimizing bed erosion associated with flood events.

Maintainance of Aquatic Food Webs

Litter provided by riparian vegetation provides the principal energy source for aquatic food webs in small streams.

Social and Economic Benefits

Flood Control

Riparian buffers can store water and reduce peak runoff during storm events.

Aesthetics

Buffer strips can provide a visually appealing "greenbelt" in otherwise developed areas. Buffers can also screen water based recreationists from upland development.

Recreation

Buffer strips can provide opportunities for hiking trails, nature study, fishing, hunting, and other recreational activities.

---

adapted from Cook College Dept. of Environmental Resources (CCDER), 1989 b.

PREVIOUS STUDIES

A number of other studies have reviewed the literature concerning buffer strips and related riparian zone management issues. Among the most useful are recent reviews by Brown et al. (1987), Budd et al. (1987), Cook College Department of Environmental Resources (CCDER 1989 a,b), Jones et al. (1988), Rodgers et al. (1988), Kuenzler (1989), Howard and Allen (1989), and IEP (1990).

INFLUENCE OF BUFFER STRIP WIDTH ON RIPARIAN FUNCTIONS

WATER QUALITY PROTECTION

Stream Temperature

Riparian vegetation is one of the most important factors controlling water temperature in small streams. Cover provided by riparian vegetation reduces warming by direct solar radiation, and insulates streams during winter months. A well developed riparian zone also stores water which, when gradually released through subsurface flow, can maintain stream flow and keep water temperatures low.

The importance of shading by riparian vegetation on stream temperature is strongly dependent on stream size. In small, heavily shaded streams, removal of riparian vegetation can dramatically increase stream temperature, particularly during summer low flow periods (Brazier and Brown, 1973; Burton and Likens, 1973; Karr and Schlosser, 1977; Feller, 1981). In large streams or rivers, where vegetation shades only a small fraction of the stream surface, riparian buffers have an insignificant effect on water temperature.

Numerous studies have found that forest clearcutting without buffer strips can greatly increase the temperature of small streams. These impacts can usually be ameliorated by leaving fairly narrow (10-20 m)* wide buffer strips.

At the Hubbard Brook Experimental Forest in New Hampshire, a 10 m strip of vegetation was very effective in buffering temperature in a small (average width = 2.9 m) mountain stream (Burton and Likens, 1973). Wide fluctuations in stream temperature between buffered and unbuffered sections of the stream were noted.

*: Data is generally presented in metric units. In instances where original data was reported in English units, the values are presented in metric units with original English units in parenthesis. Note that 1 meter (m) equals 3.28 feet, and 1 hectare (ha) equals 2.47 acres.

Aubertin and Patric (1974) found that a 10 to 20 m wide buffer strip was sufficient to maintain normal stream temperature in a clearcut West Virginia watershed. The strip was effective despite selective removal of large trees from the buffer.

In North Carolina a 12 m (40 ft) wide buffer strip was sufficient to prevent excessive temperature changes in a small mountain stream following clearcutting (see Corbett et al., 1978). The study noted a substantial drop in stream temperature immediately after the stream entered the buffered area, possibly due to an influx of cool groundwater.

Lynch and Corbett (1990) found that a 31 m (100 ft) wide selectively cut buffer strip was effective in preventing high stream temperature in a clearcut Pennsylvania watershed. Slight (< ca. $3^{\circ}F$) increases in stream temperature following clearcutting were attributed to input from an unbuffered intermittent channel that discharged into the main stream.

In a study of small mountain streams in Oregon, Brazier and Brown (1973) found that 9 m (30 ft) wide buffers were adequate for stream temperature control. Angular canopy density of buffer strips (a measure of shading) was well correlated with stream temperature control following clearcutting. Maximum shading ability was provided by a 25 m (80 ft) wide buffer strip. Data collected for similar Oregon streams by Steinblums et al. (1984) indicate that somewhat wider buffer strips are necessary to achieve maximum shading.

Hopmans et al. (1987) found that a 30 m wide buffer strip was effective in preventing stream temperatures increase following clearcutting of an Australian Eucalyptus forest.

Hewlett and Fortson (1982) found that a 7 m (20 ft) wide wind damaged buffer strip failed to prevent a large increase in stream temperature following clearcutting of a small Georgia Piedmont watershed. Increased stream temperature may have resulted from warming of shallow groundwater in exposed clearcut areas. Subsequent modelling studies by Woodall (1985) suggested that a narrow streamside buffer strip might not entirely prevent stream temperature increase following clearcutting if horizontally flowing groundwater is within 4 m of the land surface. Woodall recommended that buffer strip design take into account protection of sensitive groundwater zones, and pointed out the need for simple field techniques to identify these areas.

Barton and Taylor (1985) examined the effect of buffer strip width and length on water temperature in small (mostly < 8 m wide) streams from agricultural areas in southern Ontario, Canada. A multiple regression equation relating maximum weekly stream temperature to buffer strip length and width explained 90 percent of the variation in water temperature between sites. The relationship between stream temperature and buffer strip width and length is illustrated in Figure 1. Unlike previous studies, these results suggests that fairly wide buffer strips are necessary to maintain low stream temperatures. The authors suggest that their findings may be an artifact of how buffer strip width was measured in the study, or may reflect the influence of groundwater warming.

Suspended Sediments

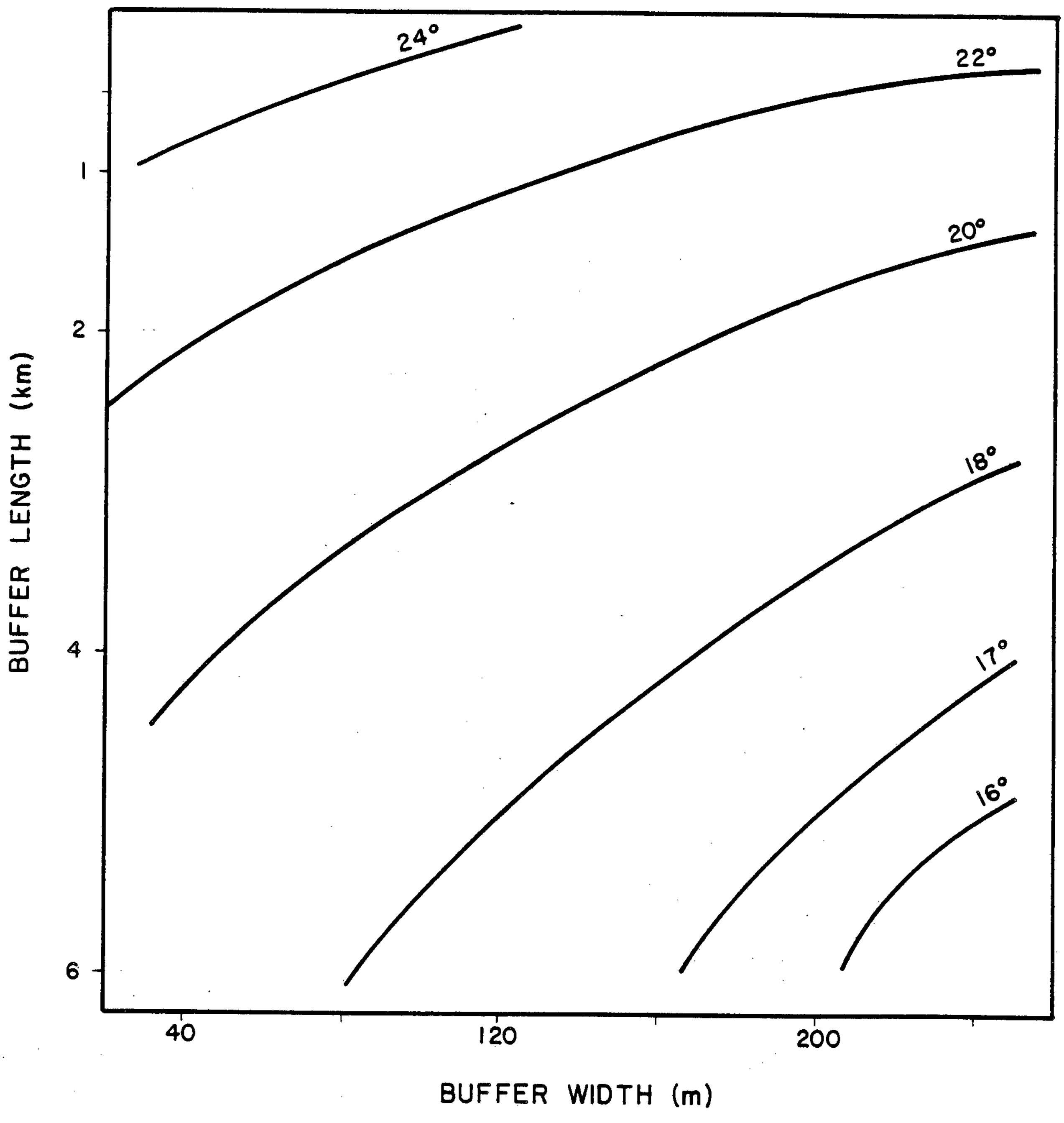
Riparian areas influence stream suspended sediment levels in several ways. Vegetative cover in riparian areas reduces potential soil erosion and filters sediment transported in surface flow from uplands. Roots of riparian vegetation bind streambanks and reduce erosion. Pools created by snags can trap substantial amounts of sediment, at least temporarily. Finally, extensive riparian areas indirectly reduce sediment transport by moderating stream discharge and bed scour during flood events.

The following discussion focuses on the ability of buffer strips to filter sediments from surface flow originating in adjacent uplands. There is general agreement from both experimental and field studies that fairly narrow buffers can protect streams from excessive sediment loading, provided that slopes are not extreme, and surface flow is not channelized within the buffer.

Buffer strip width required to filter sediments from surface flow depends on many factors. These include: 1) the desired efficiency of suspended sediment removal; 2) the hydraulic loading rate to the buffer (i.e volume of surface runoff entering the buffer per unit time and area of buffer); 3) erodibility of land surface areas upslope of the buffer, and 4) the slope, infiltration rate, and surface characteristics within the buffer. In general, sediment removal efficiency increases with infiltration rate, decreased slope, and increased density of obstructions (i.e. leaf litter, vegetation) within the buffer.

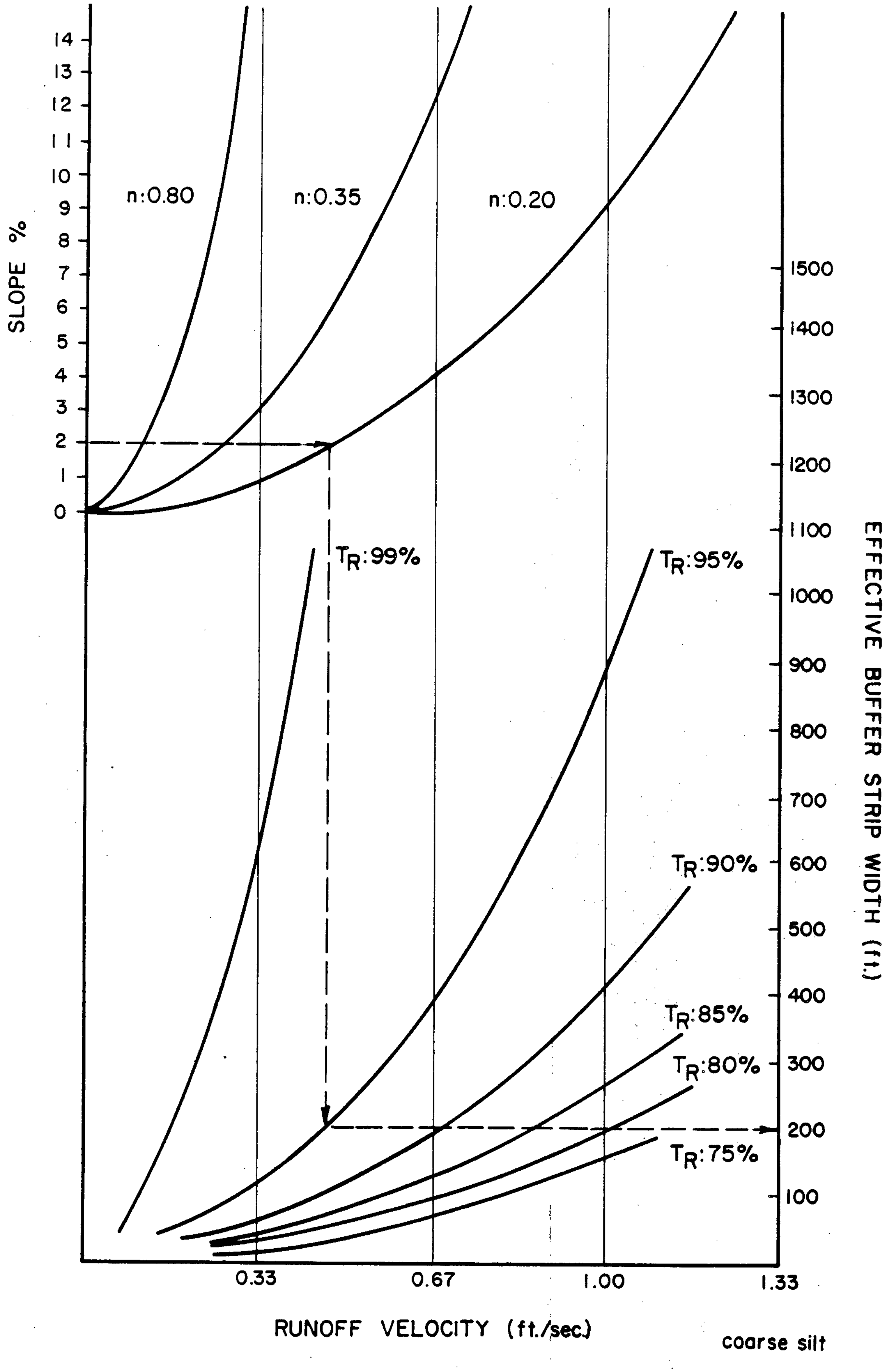
Several complex sediment transport models which can predict buffer strip width necessary to provide a given level of sediment retention are available. Wong and McCuen (1981) provide a model which relates sediment trapping efficiency to a variety of factors, including flow velocity, Manning's "n" coefficient (a measure of surface roughness), flow depth, buffer strip slope, particle settling velocity, and the spatial arrangement of vegetation. Curves were developed which relate buffer efficiency (T_r) with the width and slope of the buffer, runoff velocity, and surface roughness (Figure 2). The model suggests that under many conditions, substantial sediment retention can occur within narrow (< 60 m, 200 ft wide) buffer strips.

Figure I: Relationship Between Stream Temperture and Buffer Strip Length and Width in Southern Ontario Streams



Adapted from Barton and Taylor (1985)

Figure 2: Graphical Representation of the Wong and McCuen (1981) Sediment Retention Model



Barfield et al. (1979) and Hayes et al. (1979) developed the "Kentucky Filter Strip Model" for determining the sediment removal efficiency of grassed buffer strips. Parameters in the model include flow rate, flow duration, sediment load in the runoff, sediment particle size, and the slope and filter media density within the buffer. Field tests found that the model adequately predicted sediment discharges from a <u>Festuca</u> filter strip under field conditions (Hayes and Hairston, 1983). The model was further refined as a design aid for sediment control structures (Wilson et al., 1986).

Williams and Nicks (1988) conducted simulations to evaluate the effectiveness of grassed filter strips for sediment control using the the CREAMS ("Chemical, Runoff, and Erosion from Agricultural Management Systems") model. Filter strip effectiveness was found to be dependent on strip width, Mannings's "n", slope, slope configuration, and storm intensity. The model was found to somewhat underestimate buffer efficiency when applied in a small Oklahoma agricultural watershed.

Several simplified models are available which may prove useful for determining effective riparian buffer strip width on a practical basis.

Brown et al. (1987) provided the following model:

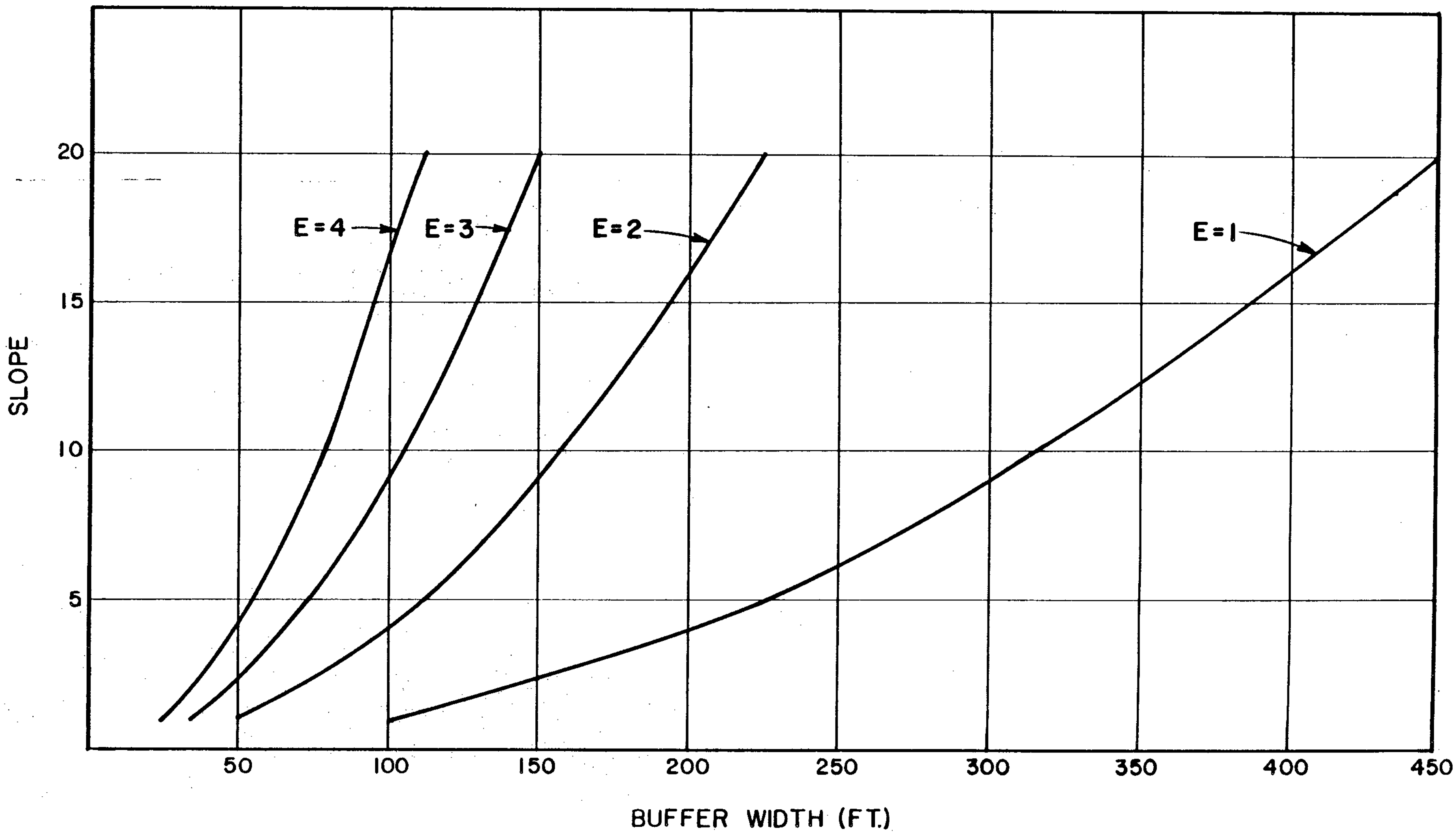
$$B_W = \frac{S}{E}^{1/2} \quad (1)$$

where: B_W = width of buffer in feet
S = average slope of land in feet per 100 ft
E = erodibility factor related to SCS erosion factor (K) as follows: K=0.1, E=4; K=0.15, E=3; K=0.17, E=2; K>0.17, E=1

Buffer strip widths required for effective sediment removal based on this equation are presented in Figure 3. A major drawback of this model is that it does not account for hydraulic loading. Intuitively, a buffer designed to treat runoff from a 100 ha area should be wider than one treating runoff from a similar 10 ha site.

IEP (1990) developed a model that determines buffer width required based on the impervious area of upland adjacent to the buffer and other site characteristics (i.e. infiltration rate). Multiple simulations using the model found that the ratio of buffer area to impervious area was a good predictor of suspended sediment removal. Removal efficiencies were also sensitive to infiltration rate. Based on this information, the following equations were developed to determine buffer area required to remove 85 percent of suspended sediments (note that alternative equations can be developed for different removal efficiencies).

Figure 3: Graphical Representation of the Brown et al. (1987) Sediment Retention Model



$$\text{For } I > 0.5: BA = 0.12(IA)$$

$$\text{For } I \geq 0.25 \text{ to } 0.5: BA = 0.017(IA)$$

$$\text{For } I < 0.25: BA = 0.31(IA)$$

where: BA = buffer area required (acres)
IA = impervious area of watershed upslope of buffer (acres)
I = infiltration rate (inch/hr) in buffer soils (based on literature values and hydrologic soil group)

The minimum buffer width required for a given site is determined using the following equation:

$$BW = (BA*43,560)/SBL \quad (2)$$

where: BW = average buffer width (feet)
SBL = buffer strip length along upland edge (feet)
43,560 = acre to square feet conversion factor

The Cook College Department of Environmental Resources (CCDER, 1989, a,b) developed a model to determine buffer strip width based on buffer slope and transit time of overland flow through the buffer. The model is as follows:

$$W = 2.5\ TS^{0.5} \quad (3)$$

where: W = buffer strip width (feet)
T = time of travel of overland flow (seconds)
S = slope
2.5 = constant for ground cover condition for forest with heavy ground litter or a meadow

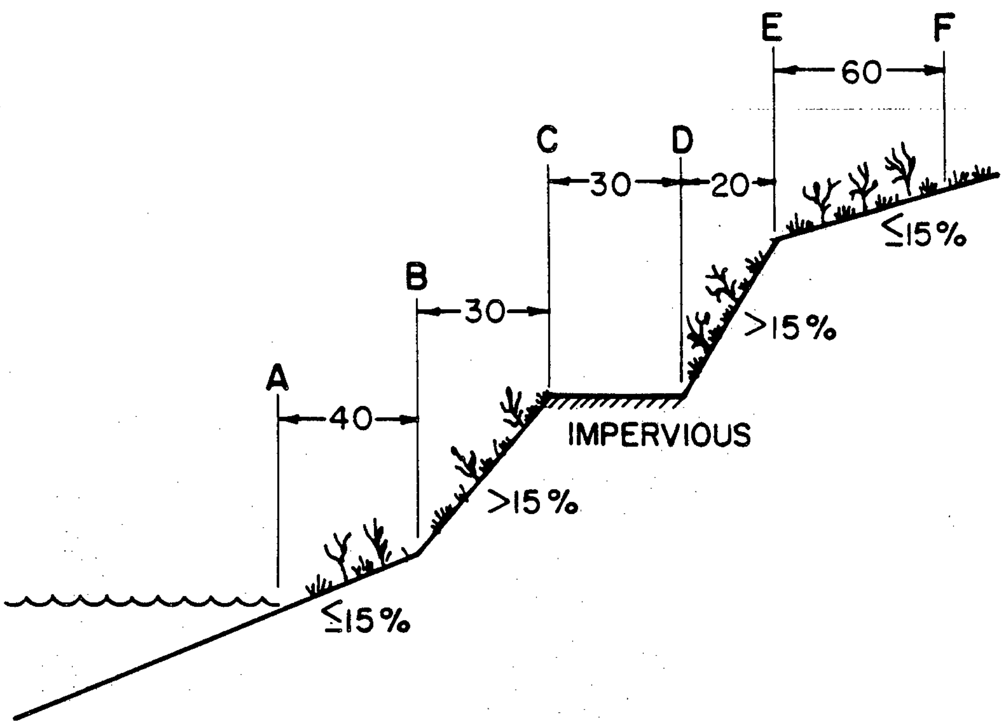
Using a base buffer strip width of 50 ft (15 m) and a base slope of 1 percent (i.e. flat) a minimum travel time can be calculated from equation 3. Substituting this value (200 sec) into equation 3 yields the following:

$$W = 500\ S^{0.5} \quad (4)$$

Using this equation, required buffer strip width varies from 50 ft (15 m) under base conditions (1 percent slope) to about 200 feet (61 m) with a 15 percent slope. When using this method, CCDER, recommends that areas within the buffer with slopes in excess of 15 percent or impervious surfaces (i.e. roadways) not be credited to the required buffer width (see Figure 4).

A number of field studies suggest that fairly narrow buffer strips are generally adequate to filter sediments from surface flow and protect streamwater quality. Karr and Schlosser (1977) reviewed several studies concerning the ability of forested buffer strips to protect streams from logging road runoff. In Idaho, Haupt and Kidd (1965) found that a 9 m wide strip was

Figure 4: Buffer Width as Determined by the CCDER (1989b) Model



100 ft. buffer excluding impervious areas and areas with slopes ≥ 15 percent

sufficient to filter out sediments during major storm events. Trimble and Sartz (1957) studied sediment movement through forested buffers below logging road culverts in the White Mountains of New Hampshire. For slopes ranging from 10 to 30 percent, sediments could be found over 30 m (100 ft) from culverts in some cases. Two-thirds of the time, however, sediments were effectively removed within 15 m (50 ft) of the culvert. Based on this data, buffer widths ranging from about 15 m for a 10 percent slope to 45 m for a 60 percent slope were recommended (see Karr and Schlosser, 1977).

Aubertin and Patric (1974) found that a 10 to 20 m buffer strip was sufficient to maintain near normal stream turbidity following clearcutting of a West Virginia watershed. Slight increases in turbidity following logging were related to increased stream discharge.

Hopmans et al. (1987) found that clearcutting of a steeply sloped (20-30 percent) forested Australian watershed had no significant impact on suspended sediment levels in a stream protected by a 30 m wide buffer strip. Export of suspended sediments from the watershed increased substantially, however, due to higher stream discharge rates following clearcutting. Low suspended sediment levels in the stream were attributed to filtering by the buffer strip, high infiltration rates on exposed clearcut slopes, and to dilution resulting from increased stream discharge.

Moring (1982) found that a 30 m wide buffer was insufficient to prevent increased sediment discharge following partial (25 percent) clearcutting of a small (304 ha) Oregon watershed. Gravel permeability in the streambed, however, was apparently not significantly effected by clearcutting.

Peterjohn and Correll (1984) found that a substantial proportion of suspended sediments were removed from surface runoff passing through 19 m of riparian forest in a small (16 ha) agricultural watershed in Maryland. Reduction in suspended sediment levels ranged from 84 percent in spring, to 97 percent in fall.

Little information if available concerning the long-term fate of sediments trapped by riparian buffer strips. Trapped sediments may be incorporated for a prolonged period of time (e.g. Lowrance et al. 1986), or be quickly remobilized during subsequent runoff or flood events. Copper et al. (1986) used cesium-137 as a marker to determine long-term sediment movements within a North Carolina coastal plain agricultural watershed. About 88 percent of sediments which had moved from uplands during a 20 year period remained in the watershed. About 80 percent of these sediments were found in the riparian zone, and 50 percent were deposited within 100 m of their entry point from adjacent uplands.

Numerous experimental studies have shown that filter strips vegetated with grass or herbaceous vegetation effectively remove suspended sediments from surface runoff (see Karr and Schlosser, 1977; Bingham, et al., 1980; Dickey and Vanderholm, 1981; Wong and McCuen, 1981). Buffers less than 30 m wide are generally adequate to remove over 90 percent of suspended solids. Dillaha et al. (1988) found that 9.1 m wide strips with 11 to 16 percent slopes removed 91 percent of suspended solids in runoff from manured test plots. Narrower (4.6 m) strips removed 81 percent of suspended solids. Schwer and Clausen (1989) found that a 26 m wide strip with 2 percent slope removed 95 percent of suspended solids from milkhouse waste. Neibling and Alberts (1979) found that a 4.9 m strip with 7 percent slope removed 95 percent of suspended sediments from surface runoff, with 91 percent of removal occurring within the first 0.6 m. Young et al. (1980) found that an 31 m (80 ft) strip removed 92 percent of suspended solids from feedlot runoff.

Vegetated filter strips work primarily by physically intercepting sediment and by reducing surface runoff volume via infiltration (Karr and Schlosser, 1977). Filter strips are much less efficient if flow is channelized within the buffer (Dillaha et al., 1989), or if vegetation is submerged by high flows (Barfield et al., 1979). Buffer may become less effective as sediments accumulate within them over time (Dillaha et al., 1988). They also are less efficient in winter than during the growing season when vegetation is well established (Schwer and Clausen, 1989).

Failure of vegetated filter strips under field conditions due to channelization within the buffer is a common problem. Dillaha et al. (1986) found that the majority of strips established on Virginia farms were ineffective because most of the flow through the filters was concentrated in channels. About 20 percent of the strips had severe localized erosion problems. Dillaha et al. (1986) recommended placement of berms perpendicular to the edge of the strip every 50 to 100 feet in order to prevent runoff from bypassing the strip. Wengrzynek (pers. commun.) also notes that buffer strips are frequently short-circuted by channelization, and that in Maine, it is impractical to maintain buffers to treat surface flow for drainage areas exceeding about 2 ha (5 acres).

Nutrients

Buffer strips can reduce the movement of nutrients from uplands into surface waters. The primary processes involved include: 1) retention of sediment bound nutrients transported by surface runoff, 2) uptake of soluble nutrients by vegetation and microbes, and 3) absorption of soluble nutrients by organic or inorganic soil particles. Sediment retention seems to be main process responsible for removing phosphorus (at least initially), while denitrification is the primary process responsible for nitrogen (nitrate) removal.

The nutrient removal efficiency of buffers probably depends on many factors. These include sedimentation rates, surface and subsurface drainage characteristics, soil characteristics (particularly oxidation-reduction potential, organic content, and temperature), the successional status of vegetation, and nutrient loading rate from uplands per unit area of buffer.

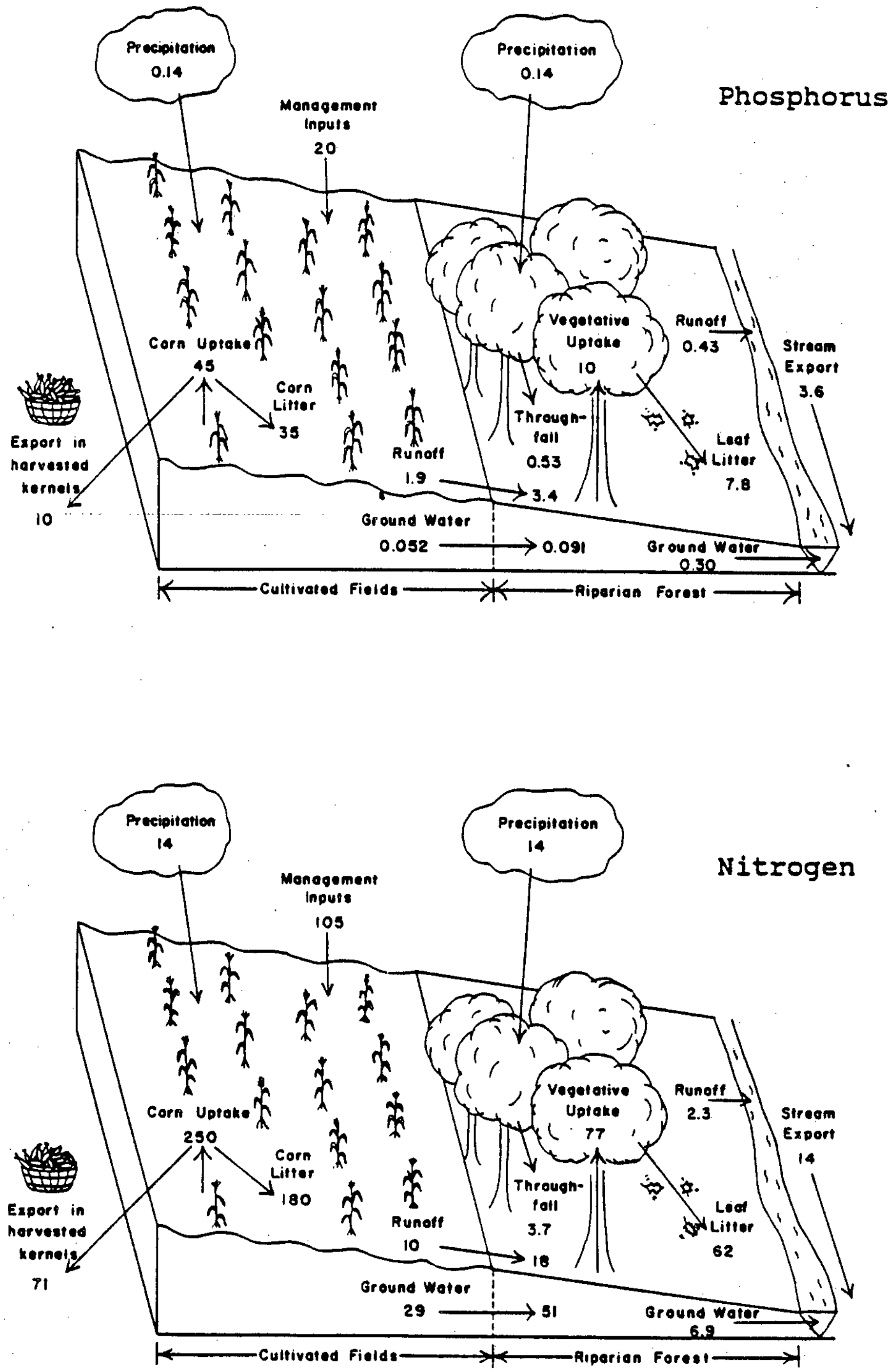
A number of studies provide information about the nutrient removal efficiency of buffer strips. There is general agreement that fairly narrow buffers effectively remove nitrate from both surface and groundwater flow. Buffers also effectively remove sediment bound phosphorus, but appear less efficient at removing soluble phosphorus from surface runoff or groundwater. Buffer width required depends on both removal efficiency and on desired water quality standards for effluent, and for the receiving water body.

Peterjohn and Correll (1984) developed nutrient budgets for a small (16 ha) agricultural watershed in Maryland. Forested riparian areas within the watershed retained 89 percent of nitrogen inputs contributed by groundwater, bulk precipitation, and surface runoff (see Figure 5). Passage through about 50 m of riparian forest drastically reduced concentrations of dissolved and particulate nitrogen. Most of the reductions occurred within the first 19 m of the buffer. Uptake by vegetation may have accounted for about one-third of the nitrate removal. Presumably the remainder of nitrogen was lost via denitrification

It was unclear if the riparian buffer effectively retained phosphorus. Most of the phosphorus (80 percent) entering the riparian forest appeared to be retained (see Figure 5). Also, concentrations of particulate phosphorus in surface runoff were drastically reduced within the first 19 m of the buffer. Levels of dissolved phosphorus in surface runoff, however, changed little within the buffer, and phosphorus levels in groundwater increased during passage through the buffer. Furthermore, discharge of phosphorus from the whole watershed measured at a weir was similar to estimated discharge from agricultural fields within the watershed. This suggests that overall, the riparian forest may have trapped little phosphorus (Jordan et al., 1986).

Lowrance et al. (1983, 1984, 1984a, 1984,b) developed a nutrient budget for a large (1568 ha) agricultural watershed in Georgia. About 45 percent of the basin was devoted to agriculture, while 30 percent of the watershed was occupied by riparian forest (no information about buffer zone width was provided). On a short-term basis, the riparian zone retained 68 percent of nitrogen and 30 percent of phosphorus entering via precipitation, subsurface flow, and nitrogen fixation. No estimate was available for nutrients input via surface runoff, but these inputs were assumed to be small. Denitrification within the riparian zone accounted for most (ca. 80 percent) of nitrogen removal.

Figure 5: Phosphorus and Nitrogen Budgets for a Maryland Agricultural Watershed



Values in Kilograms per Hectare per Year

Adapted from Peterjohn and Correll (1984)

Forested buffer strips as narrow as 16 m were found to remove virtually all nitrate in subsurface drainage from cultivated North Carolina fields (Jacobs and Gilliam, 1985; Cooper et al., 1986). Nitrate levels were reduced within the buffer from about 7.5 ppm to less than 0.2 ppm. Soils in the buffers were poorly drained, highly organic, and anaerobic most of the time. These conditions are conducive to denitrification, and most of the nitrate loss was attributed to this process.

Schnabel (1986) found that nitrate concentration in groundwater was substantially reduced during passage through 18.5 m of riparian forest adjacent to a small (first order) Pennsylvania stream. Nitrate levels were reduced by about 40 percent in May, and by more than 90 percent in June and July. A 27 m wide grassy strip on the opposite side of the stream reduced nitrate concentrations by about 10 percent in May, and about 60 percent in June and July. The reason for relatively low nitrate removal efficiency in the grassy buffer is unknown. Average nitrate levels entering the grassy strip, however, were much higher than those entering the wooded strip (17.2 vs. 4.3 ppm), and may be partly responsible for the difference.

Lynch and Corbett (1990) found elevated nitrate levels in stream water draining a clearcut Pennsylvania watershed despite the presence of a 31 m (100 ft) wide selectively cut buffer strip. Average annual nitrate levels of were still significantly higher 11 years after clearcutting, but declined to background levels during the growing season by the seventh year after cutting. Elevated nitrate levels may have been due to blowdown of portions of the buffer and input from an unbuffered intermittent channel.

Aubertin and Patric (1974) found that discharge of nitrogen (nitrate and ammonium) and total phosphate increased from a clearcut West Virginia watershed despite the presence of a 10 to 20 meter wide buffer strip. Increased discharge of nutrients following clearcutting appeared related to both increased nutrient concentrations in stream water (especially total phosphorus) and increased stream discharge rate. Natural revegetation of the watershed was rapid, and discharge of total phosphorus and ammonium declined sharply relative to a control watershed within two growing seasons. Nitrate discharge remained elevated, however.

The longterm effectiveness of forested riparian buffer strips as nutrient filters in unknown. Heavy floods may export substantial quantities of nutrients sequestered in sediments and litter. Riparian sediments may also release nutrients during seasonal high flow periods. Cooper et al. (1986) found that floodplain swamps were net long-term sinks for total phosphorus, but released available phosphorus to overlying waters during flood events. Also, nutrients in sediments and dead vegetation may be gradually released (mineralized) over time (Lowrance et al., 1984) and transported from buffers. This may be especially true for phosphorus, which is mobile under anaerobic conditions in wetland soils.

As riparian ecosystems mature, net annual nutrient uptake in vegetation may decline, and buffers may become less effective filters (Omerick et al., 1981). Also, nutrient levels in soils may reach an equilibrium point at which no further net accumulation occurs without additional accrual of sediments or organic material. Because forested buffers appear to reduce nitrate levels primarily by denitrification (rather than accumulation in biomass or soils), the capacity of buffers to retain nitrogen may remain rather stable over time, unless hydrologic conditions change.

In order to maintain the ability of riparian buffers to assimilate nutrients it may be necessary to periodically remove nutrients sequestered in vegetation (Lowrance et. al., 1983). Selective cutting of trees would also open up the forest canopy and allow development of more vigorous understory vegetation (which could improve sediment retention). No studies, however, have closely looked at the effectiveness or impacts of this management practice, and Fail et al. (1986) found that even fairly mature riparian forests retain a capacity to accumulate excess nutrients. Also, unless properly controlled, selective logging could destabilize stream embankments, lead to increased erosion or channelization within buffers, and have adverse impacts on plant and wildlife species. If selective cutting were practiced it would be prudent to remove vegetation primarily from the upland edge of the buffer zone.

Many short-term experimental studies have evaluated the ability of vegetated filter strips to remove nutrients in runoff from feedlots or other point sources. These studies have generally found that strips with uniform surface flow are very effective in retaining both total nitrogen and total phosphorus (see Table 2).

Filter strips appear more effective at removing sediment bound nutrients, than soluble nutrients, and in some instances strips may actually be net exporters of soluble nutrients (e.g. Dillaha, et al., 1989). Filter strips are less effective in the winter, particularly during snowmelt, than during the growing season (Schwer and Clausen, 1989). Nutrient removal efficiencies also decline if flow within the buffer is channelized (Dillaha, et al., 1988; Dickey and Vanderholm, 1981). As is the case for forested buffers, the long-term effectiveness of filter strips is questionable. Periodic harvests of vegetation to remove nutrients may be required to maintain long-term buffer efficiency.

Although vegetated filter strips may be highly efficient at removing nutrients from wastewater, the strips may still export unacceptable amounts of nutrients to receiving waters. Filter strips may be ineffective, despite high removal efficiencies, if nutrient loading rates to the strip are high or if receiving waters are particularly sensitive to nutrient loading. Clausen and Meals (1989), for example, found that filter strips which removed a high percentage of phosphorus from agricultural wastes would fail to protect one-third of Vermont streams from eutrophication (see Table 3).

TABLE 2: Nutrient Retention by Vegetated Filter Strips

Effluent Source	Filter Width (m)	Slope (%)	% Reduction[1] N	% Reduction[1] P	Reference
Manure Treated Plots	4	-	-	62	see Thompson et al., 1979
Feedlot	35-41	4	84	76	Young et al., 1980
Feedlot Settling Basin Effluent	91	0.5	97[2]	96	Dickey and Vanderholm, 1981
Feedlot Settling Basin Effluent	60[3]	2	74	73	Edwards et al., 1983
Manure Treated Plots	9.1	11	77	80	Dillaha et al., 1988
	9.1	16	71	57	
	4.6	11	61	63	
	4.6	16	67	52	
Milkhouse Wastewater	26	2	92[2]	89	Schwer and Clausen, 1989

1. Reductions on mass balance basis of total nitrogen and total phosphorus.
2. Total Kjeldahl nitrogen.
3. Two successive 30 m strips.

TABLE 3: Percentage of Vermont Streams Expected to Have Phosphorus Concentrations Exceeding 20 ug/l Given One Source Per Watershed (adapted from Clausen and Meals, 1989).

Source	Total P in Effluent Concentration (mg/l)	Total P in Effluent Daily Export (g/d)	Percent of Streams
Milkhouse Waste (raw)	79.9	98.9	64
Milkhouse Waste (treated)	11.4	11.3	32
Barnyard Runoff (raw)	20.1	79.7	58
Barnyard Runoff (treated)	18.8	44.0	41

note: wastes treated by vegetated filter strips

Pesticides

Pesticides applied to agricultural fields, forests, and other upland areas can enter streams via surface runoff, aerosol drift, and groundwater discharge. Buffer strips can reduce pesticide discharges into streams, but there is limited information in the literature upon which to base recommended buffer strip widths. Presumably necessary buffer strip width depends on stream size, pesticide mobility (which depends on pesticide type, rate and method of application, soils, topography, weather conditions, and other factors), and pesticide toxicity to aquatic biota.

Asmussen et al. (1977) found that a 24.4 m grassed buffer reduced 2,4-D levels in surface runoff from narrow agricultural plots. About 70 percent of the 2,4-D entering the buffer was removed.

Field studies in Canada indicate that a 15 m buffer strip may be suitable to protect aquatic habitat from ground applied synthetic pyrethroids. A 100 m buffer strip provides adequate protection with aerial application (Nriagu and Lakshminarayana, 1989). Although highly toxic to aquatic insects, pyrethroids are highly adsorptive on soil particles, and unlikely to reach streams via leachate. Another study, however, found substantial (20 percent) mortality of mosquito larvae placed in pools 50 m downwind from a pyrethroid (permthrin) aerial spray line. Little mortality (2.2 percent), however, was noted at 100 m.

Lavy et al. (1989) found that a 15 m buffer strip failed to prevent surface-applied hexazinone (a widely used herbicide) from reaching a small stream in a steeply sloped forested West Virginia watershed. During the first two years after application, about 5 percent of the herbicide reached the stream, with highest concentrations in stream waters occurring during storm events. Hexazinone is likely to be fairly mobile, because it is water soluble, and has a low tendency to adsorb onto soil particles.

Rohde et al. (1980) found that 86 to 96 percent of trifluralin (a herbicide) entering an experimental 24 m wide grassy filter strip was retained by the strip. Infiltration within the strip accounted for about one third of the lost trifluralin. Retention and infiltration rates were somewhat higher under dry conditions, than when the strip was wet.

STREAM HABITAT

Streambank Stability

Although the importance of riparian vegetation in maintaining streambank stability is widely recognized (e.g. Beschta and Platts, 1986) there is little guidance to suggest how wide buffers must be to adequately protect embankments. Intuitively, it seems that fairly narrow (< 5 m) forested buffers should serve to hold embankments in place, at least over the short-term.

In a survey of 25 short sections of streams in developed areas of central New Jersey Whipple et al. (1981) found a correlation between streambank/bed erosion and buffer strip width. Substantial streambank erosion rarely occurred when buffer strips where wider than 50 feet, but almost always occurred when buffers were more narrow. The apparent relationship between stream stability and buffer width may have been confounded with land use, since highly developed watersheds (with high runoff and erosion potential) were apt to have narrow buffers.

Erman et al. (1977) found that 30 meter wide buffer strips were adequate to maintain streambank stability in low order northern California streams.

Stream Structure

In forested areas, large woody debris ("snags"), can be a critical structural component of stream ecosystems. Snags can create pools, trap sediments and retard scouring of stream beds during high flows (Sullivan et al., 1987; Bisson, et al., 1987), and provide excellent habitat for fish and invertebrates (see Wallace and Benke, 1984). Habitat provided by snags is most important in small, low-order streams, but can also be important in higher-order streams with low gradients (Benke et al., 1985).

Few studies have determined buffer strip width required to maintain snag habitat in streams. Based on data from six Alaskan streams, Murphy and Koski (1989) recommended that a 30 meter wide buffer strip be left on both sides of streams to maintain a constant level of instream woody debris. Their study found that nearly 50 percent of large woody debris in Alaskan streams originate from within one meter of the stream bank. Ninety five percent of debris originated within 20 meters of the streambank, and 99 percent within 30 m. Bottom et al. (see Budd et al., 1987) also found that most woody debris in Oregon streams is derived from within 31 m (100 ft) of the stream bank.

Food Supply

Organic material derived from riparian areas is the main energy source for aquatic food webs in most small to medium sized streams (Minshall et al., 1985). Leaves are of principal importance but, twigs, fruits, terrestrial insects, and wood are also utilized by stream detritivores.

van Groenwood (see Holler 1989) suggests that few trees further than 15 m from the streambank are likely to contribute significant leaffall to streams. The contributing area of the riparian zone probably varies somewhat with steepness of sideslopes (Cummins et al., 1989), and the type of vegetation (i.e. conifers vs hardwoods). Because most leaves falling into streams may be retained within several hundred meters of their entry point (Cummins et al., 1989), a nearly continuous buffer strip of riparian vegetation may be essential to maintain riparian based aquatic food chains.

AQUATIC BIOTA

Invertebrates

Because buffer strips can greatly influence water temperature and other habitat variables in low order streams, buffers probably have a considerable impact on fish and invertebrate communities. Few studies, however, have looked closely at the effect of buffer strip width on stream biota.

Newbold et al. (1980) studied the impacts of logging with and without buffer strips on aquatic invertebrates in low order northern California streams. Invertebrate community structure was not significantly different between undisturbed streams and those with buffer strips $\geq$ 30 m wide. For streams protected with narrower buffer strips (< 30 m), some changes in community structure were noted. Among these streams, there was a strong positive correlation between buffer strip width and species diversity. Follow up work 5 to 6 years after the initial sampling (6 to 10 years after logging) found that streams with narrow buffers showed little evidence of recovery (Erman and Mahoney, 1983). Although buffers less than 30 m wide were ineffective overall, in some instances where logging was conducted with care, narrower buffers adequately protected invertebrate communities.

In northern New England 8 to 9 m wide buffer strips were insufficient to prevent logging impacts on invertebrate and periphyton communities in small (1.8 to 2.4 m wide) streams (Noel et al., 1986). Invertebrate densities in buffered streams in clearcut watersheds were 2-4 times those in undisturbed streams. Periphyton densities also appeared much higher in clearcut streams, despite the presence of buffer strips. Increased periphyton density was probably caused by increased light availability in the inadequately buffered streams.

Fish

Very little specific information is available concerning the influence of buffer strip width on fish. Studies in the Pacific northwest found that a 30 m wide buffer strip prevented significant logging related impacts on fish populations (see Newbold et al., 1980 for references; original reports not seen).

A series of studies conducted in southeastern Alaskan streams compared fisheries resources in clearcut, buffered, and uncut (old growth) watersheds (Heifetz et al., 1986; Johnson, et al., 1986; Murphy et al., 1986; Thedinga et al., 1989). Although these studies found that buffer strips can strongly influence stream habitat and fish populations, conclusions concerning effective buffer strip width are difficult to make because buffer widths varied widely (from ca. 10 to 130 m), and some buffers experienced blowdowns.

In some instances wide riparian buffers may effect fish by moderating the frequency and intensity of flood events. Erman et al. (1988) found that lack of forested riparian vegetation or very thin buffer strips led to increased snow depth along the banks of a Sierra Nevada stream. As a result, the snowbanks confined stream flow, and exacerbated the severity of winter floods. Severe flooding caused high mortality among benthic fish species and demersal eggs of fall spawning species such as brook trout.

RIPARIAN BIOTA

Wildlife

Although the importance of riparian areas as wildlife habitat is well documented (see Brinson et al., 1981; Motroni, 1980; Hopper, 1989), little information is available upon which to firmly base buffer strip width recommendations. At a minimum, buffers should be wide enough to provide habitat for species adapted to both riparian "edge" and "interior" habitats. Also, the buffer area (length x width) should be large enough to provide adequate breeding and foraging habitat. Although contiguous buffers less than 200 m wide may be adequate for many species (see below), much larger buffers may be needed for some mammals (e.g. black bear) and raptors which require large home ranges. In order to maintain these species, a regional approach which preserves large tracks ("islands") of riparian habitat interconnected by relatively narrow riparian travel corridors may be needed (Noss and Harris, 1986, Noss 1987; Lines and Harris, 1989; but see Simberloff and Cox, 1987).

A number of studies provide some guidance concerning buffer strip width required to support wildlife populations. In a review of early literature, Brinson et al. (1981) found that riparian vegetation within about 200 m of streams (or open water) was most heavily used by many wildlife species. Many riparian mammals, reptiles, and amphibians were active primarily within 60 m of water. Some species such as mink and belted kingfisher were found to establish territories within very narrow riparian buffers. Others such as Cooper's hawk and red-shouldered hawk were found only where buffers were at least 100 m wide.

In Iowa, Stauffer and Best (1980) found that species richness of breeding bird communities increased with the width of wooded riparian buffers. Buffers widths required to support selected species are given in Table 4.

In Maine, Hooper (pers. commun.) found that species richness of breeding bird communities increased with distance from streams in both upland and floodplain forests. Overall for both forest types, about 90 percent of breeding species were found to occur within 175 m of streams. For floodplain forests, the highest average density of breeding species occurred at the closest sampling station to streams (25 m). For upland forests, the highest average density of breeding birds occurred further from streams (ca. 125 to 175 m). Lower densities probably occurred near streams in upland forests because some forest interior species were avoiding the riparian edge (Hooper, pers. commun.).

In Virginia, Tassone (see Howard and Allen, 1989) found that many forest-interior species were most common when buffers exceeded 62 m in width.

In the North Carolina piedmont, Simpson (1969) found that the prothonotory warbler was generally absent from waterways when forested buffers were less than 30 m wide.

Various studies suggest that wood duck nests occur most commonly within 200 m of permanent of water or wetlands (see Lowney and Hill, 1989).

Studies reviewed by Brinson et al. (1981) suggest that 5 to 6 ha riparian "islands" are needed to support near maximum songbird diversity. Larger areas are required to support most raptors. Gaines (1974) suggested that 10 ha riparian areas were required to support species such as red-shoulderd hawk (Gaines, 1974). Harris (1989) suggests that at least 30 acre tracts of forested wetlands are needed to maintain viable populations of interior orientated species.

In the Cascade Mountains of Oregon riparian buffers ranging from 9-20 m at one site, to 67 m at a second site, were sufficient to prevent significant impacts on small mammal communities (Cross, 1985). Dickson and Huntley (1987) concluded that a riparian buffer at least 55 meter wide is needed to maintain squirrel populations in Texas.

TABLE 4: Minimum Riparian Buffer Strip Widths Required to Support Breeding Bird Populations in Iowa (adapted from Stauffer and Best, 1980).

Species	Buffer Width (m)
Cardinal	11
Blue jay	15
Black-capped chickadee	15
Downy woodpecker	15
White-breasted nuthatch	17
Eastern wood pewee	20
Great crested flycatcher	35
Brown thrasher	40
Hairy woodpecker	40
Red-eyed vireo	40
Red-bellied woodpecker	90
Warbling vireo	90
Tufted titmouse	100
Wood thrush	135
Blue-gray gnatcatcher	150
Ovenbird	175
Scarlet tanager	200
American redstart	200
Rufous-sided towhee	200

Little information is available concerning how wide buffer strips need to be in order to serve as effective travel corridors. Although very wide corridors may be required for large mammals (e.g. black bear), corridors less than 200 m wide may be suitable for most other species. Riparian corridors should be wide enough to include some upland habitat, so that they are useful to both riparian and upland species (Forman, 1983).

Based on a literature review, Howard and Allen (1989) recommended that buffers along perennial streams in flat southern forested wetlands be at least 60 m wide to provide wildlife habitat. On larger streams (> 10 m) they recommended a 60 m buffer on both sides of the stream, while in smaller streams the 60 m buffer could be divided between the two sides.

Vegetation

There is very little information available about how wide buffer strips must be in order to maintain riparian plant community diversity. In order to maximize diversity, however, buffers should probably extend from the stream edge to upland. In the hypothetical example given in Figure 6, plant species distribution in riparian areas varies from stream edge to upland along a complex environmental gradient. In this example, a 50 m wide buffer is sufficient to provide habitat for riparian edge species (A, B, D), riparian-interior species (C,E,F), and upland edge species (G,H,I).

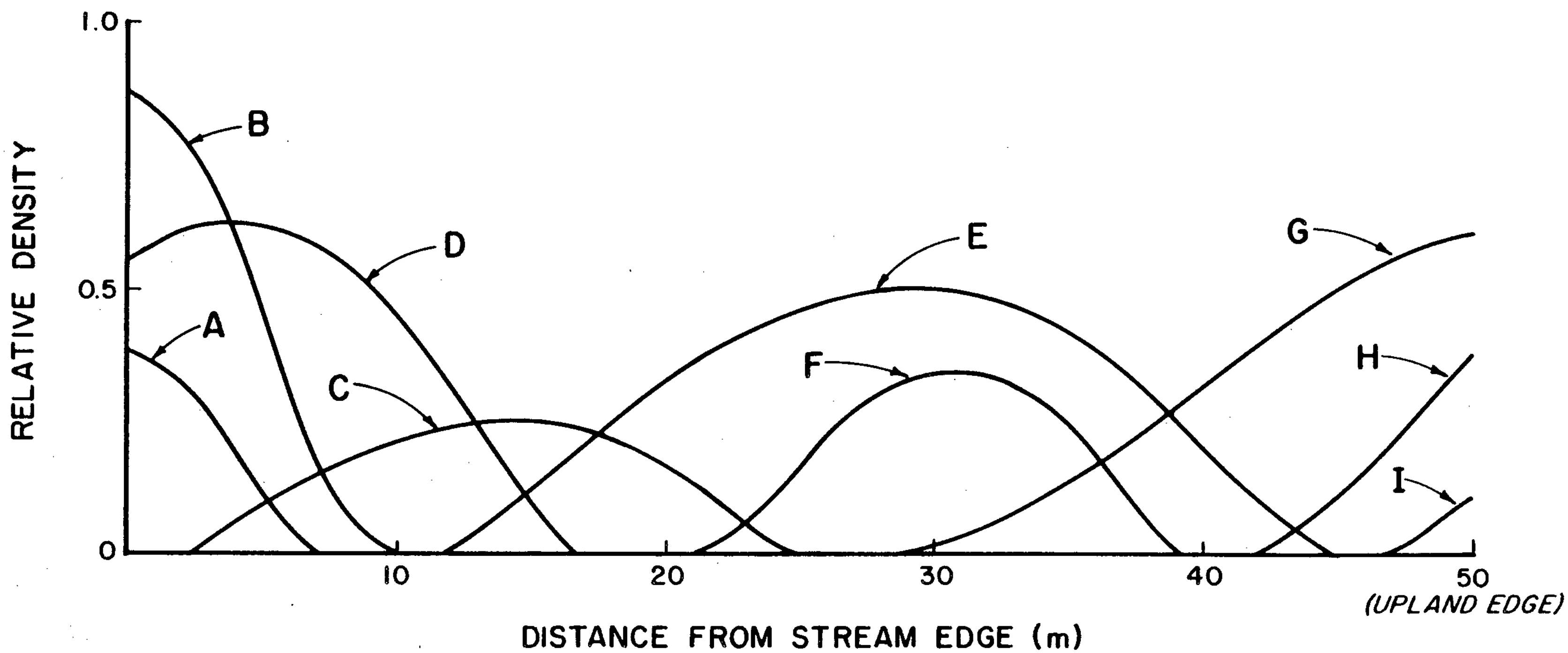
Some relevant information is available from upland habitats. In Wisconsin forests Ranney et al. (1981) suggests that forest corridors must be at least 30 m wide to sustain sugar maple, an interior orientated species. Other studies suggest that upland hedge rows must be at least 12 m wide in order to maximize forest herb diversity (see Forman and Godron, 1986).

Modelling studies of riparian forest dynamics (i.e. Hanson et al., 1990), may eventually provide guidance concerning the management of riparian areas to preserve plant community diversity.

AESTHETICS

There appears to be no information in the literature concerning how wide buffers should be to protect the aesthetic values of streams or rivers. For National Wild and Scenic Rivers, Congress mandated a one-quarter mile (400 m) buffer (P.L. 90-542). In many cases, however, narrower buffers are probably sufficient to screen upland development from streamside vantage points. Required buffer width probably varies from site to site with topography and the density of riparian vegetation.

Figure 6: Vegetation Diversity and Buffer Zone Width



LONG-TERM BUFFER STRIP STABILITY

In order for forested buffer strips to be effective over the long term, the strips must be wide enough to insure that they are physically stable. The most frequent cause of buffer strip failure is wind damage. Other factors such as streambank instability, slope failure, and insect infestations can also damage buffers (Steinblums et al., 1984).

A variety of factors influence the susceptibility of trees in buffer strips to windthrow. Buffers dominated by species with shallow root systems (e.g. spruce, fir, and aspen) are likely to be more susceptible to windthrow than those dominated by species which tend to have deeper root systems (e.g. hickory and oak). Information concerning the root structures of common trees and large shrubs occurring in riparian areas in the northeastern United States is presented in Table 5. Many common riparian species are weak wooded or subject to wind throw.

Soil conditions also influence buffer strip susceptibility to windthrow. Windthrow is more frequent when trees are growing on shallow soils or on heavy, clay soils in which roots cannot penetrate deeply enough to gain a firm foothold (Toumey and Korstian, 1947). Also, trees growing on soft wetland soils are more susceptible to windthrow. This is partly because these soils do not offer trees firm support, and partly because trees growing in wet soils tend to have shallow root systems.

Historical factors also influence the susceptibility of buffer strips to windthrow. Immediately following clearcutting, trees at the edge of buffer strips are likely to be more susceptible to windthrow than those in older buffer strips which have been exposed to wind stress for a prolonged period of time. Periodic exposure to wind causes anatomical changes in woody tissues when strengthens trees and make them less susceptible to wind damage (Wenger, 1984).

Selective thinning of forested stands may increase susceptibility to windthrow (Toumey and Korstian, 1947; Wenger, 1984). Although no data is available for buffer strips, it is likely that selective cutting within buffers also increases the risk of damage. Selective cutting of unstable trees occurring along streams, however, would improve streambank and buffer stability.

There is little guidance in the literature concerning how wide buffer strips should be in order to insure a reasonable degree of stability. Steinblums <u>et al</u>. (1984) examined the stability of 40 buffer strips left along streams during logging operations in coniferous forests of Oregon's Cascade Mountains. Buffer strips ranged in width from about 10 to 40 m, and were 1 to 15 years old. Buffer strip stability was measured as the percentage of initial timber volume remaining in the buffer, and ranged from 22 to 100 percent. Wind damage accounted for over 90

TABLE 5: Root Structure of Common Trees in Riparian Areas of the Northeastern United States

Common Name	Scientific Name	Root Structure			Suceptibility to Wind/Ice Damage
		Shallow Lateral	Deep Lateral	Taproot	
Balsam fir	Abies balsamea	x			F(wt)
Boxelder	Acer negundo		x		F(ww)
Red maple	Acer rubrum	x			F(ww)
Silver maple	Acer saccharinum	x			F(ww)
Mountain maple	Acer spicatum	x			F(ww)
Alder	Alnus rugosa	x			F(wt,ww)
Yellow birch	Betula lutea		x		I
Paper birch	Betula papyrifera		x		I
Gray birch	Betula populifolia	x	x		F(ww)
Bitternut hickory	Carya cordiformis			x	I
Shagbark hickory	Carya ovata			x	I
Common hackberry	Celtis occidentalis		x		I
Alt. leaved dogwood	Cornus alternifolia	x			F(wt,ww)
White ash	Fraxinus americana	x			F(wt)
Black ash	Fraxinus nigra	x			F(wt)
Green ash	Fraxinus pensylvanica lan.	x			F(wt)
Eastern black walnut	Juglans nigra			x	I
Eastern larch	Larix laricina	x			F(wt)
Red mulberry	Morus rubra		x	x	F
Eastern popular	Populus deltoides	x			F(ww)
Black cherry	Prunus serotina		x	x	I
White oak	Quercus bicolor	x			I
Pussy willow	Salix discolor	x			F(ww)
Black willow	Salix nigra	x			F(ww)
American elm	Ulmus americana	x	x		I
American hophornbeam	Ostrya virginiana		x	x	I
White spruce	Picea glauca	x			F(wt)
Black spruce	Picea mariana	x			F(wt)

Adapted from Hightshoe (1978)

F: frequent; I: infrequent; wt: windthrow; ww: weak wood or branches percent of timber loss. Buffer strip stability was not significantly correlated with buffer strip width, but was correlated with several topographic variables, most of which were related to wind exposure. Species differed in susceptibility to windthrow, and smaller individuals of most species tended to be more windfirm. Buffer strip age was not correlated with stability, suggesting that trees susceptible to windthrow tend to be lost soon after clearcutting.

To reduce susceptibility to windthrow, Lynch and Corbett (1990) suggest that streamside buffers in Pennsylvania should be 1.5 times the average height of trees.

In Maine, Kaohn (pers. commun.) notes that many 30 m (100 ft) wide spruce-fir buffer strips left after clearcutting experience blowdowns. He suggests that even a 45 m (150 ft) buffer may not be wide enough to insure stability, unless the buffer is sheltered from prevailing winds.

Even very wide buffer strips may not be stable over the long-term because of channel instability or rare, catastrophic events such as major floods and windstorms. Many streams have floodplains that are much wider than the actual stream channel. Overtime, erosional and depositional processes cause stream channels to meander back and forth across floodplains. During this process existing riparian vegetation is destroyed and new riparian habitat created. The rate of channel movements are highly variable, and buffer width needs to be determined on a case by case basis.

In central and southern New England hurricanes capable of causing catastrophic damage to forests occur every 100 to 150 years (see Foster, 1988). Regardless of width, riparian buffer strips would undoubtedly suffer severe damage during such events.

Little is known about the effect of blowdowns on the functional values of buffer strips. Cromack et al. (1979) suggests that at least some buffer strip values may remain after a strip experiences a blowdown. Murphy et al. (1986) found high densities of coho salmon parr within buffered reaches of Alaskan streams that had experienced severe blowdowns.

APPROACHES USED TO DETERMINE BUFFER STRIP WIDTH

LAWS AND REGULATIONS

A number of states and numerous local governments have enacted rules or regulations concerning buffer strip width (see Table 6). These regulations generally reflect both technical and socio-economic considerations. Standard buffer widths are often mandated, although in a few cases buffer width varies with stream quality, topography, or upland land use.

TABLE 6: Buffer Strip Width Mandated in Some State or Local Laws and Regulations.

Water Resource and Location	Buffer Width (m)	Notes
Reservoirs		
Connecticut	77	measured from high waters
New York	31	minimum recommended
	15-167	required setbacks for various land uses
Lakes		
Maine	77	fixed width
Streams		
Baltimore Co., MD	min. 23	variable, depends on stream quality, slope, delineation, of 100 YFP and wetlands.
Durham Co., NC	15-31	
Idaho	23	forestry, streams suitable for spawning/rearing fish
	1.5	forestry, minor streams
Maine	23	
Massachusetts	46	proposed
	8	proposed for densely developed areas
Montgomery Co., MD	8+100 YFP	applies to construction
Maryland	31	
New Jersey	8	general
	17	trout streams
North Carolina	23	existing
	62	proposed
Orange Co., NC	15 to 100 YFP	variable with slope
Oregon	3x stream width (min 7.6, max 31)	forestry, some activities allowed within buffer
Wisconsin	92	

*: values taken from Aucutt (1980), Rogers et al. (1988), CCDER (1989 b), and Ice (1990).
100 YFP: 100 year floodplain.

BUFFER DETERMINATION METHODS

Because riparian areas are so variable, there is a general consensus that fixed or standardized buffer widths are inadequate to protect riparian resources. Determination of appropriate buffer widths should consider factors such as topography, existing riparian zone development, water quality protection goals, and regional management objectives.

Numerous approaches for determining buffer strip width on a site by site basis have been proposed. A number of recently developed methods will be described in detail below. Other approaches are outlined in CCDER (1989 b). Most of the approaches are geared towards protection of water quality and fisheries resources.

A number of studies vary buffer width with watershed topography. Trimble (1959), for example suggested that buffers for logging roads have a minimum width of 8 m (25 ft), with 0.6 m (2 ft) added per one percent increase in slope. Several other similar approaches are described by CCDER (1989 b). In some studies a matrix was developed which varies buffer width based on both stream class and slope (Table 7).

Cohen et al. (1987) outlined a series of recommendations for protecting stream corridors in developing areas of the Pacific Northwest. A 15 m buffer width was recommended to protect most types of aquatic habitat. This width reflected a compromise between the technical literature, which supported 30 m wide buffers (Budd et al., 1987), and the political realities of imposing larger buffer widths in areas facing heavy development pressure. Buffers were expanded where necessary, however, to include wetlands and areas with slopes greater than 40 percent.

IEP (1990) developed draft guidelines for determining vegetative buffer strip width required to protect inland water quality within Rhode's Island's Narragansett Bay basin. The guidelines are intended primarily to reduce impacts of stormwater drainage from urban and suburban developments, and do not explicitly provide for wildlife habitat or other buffer functions.

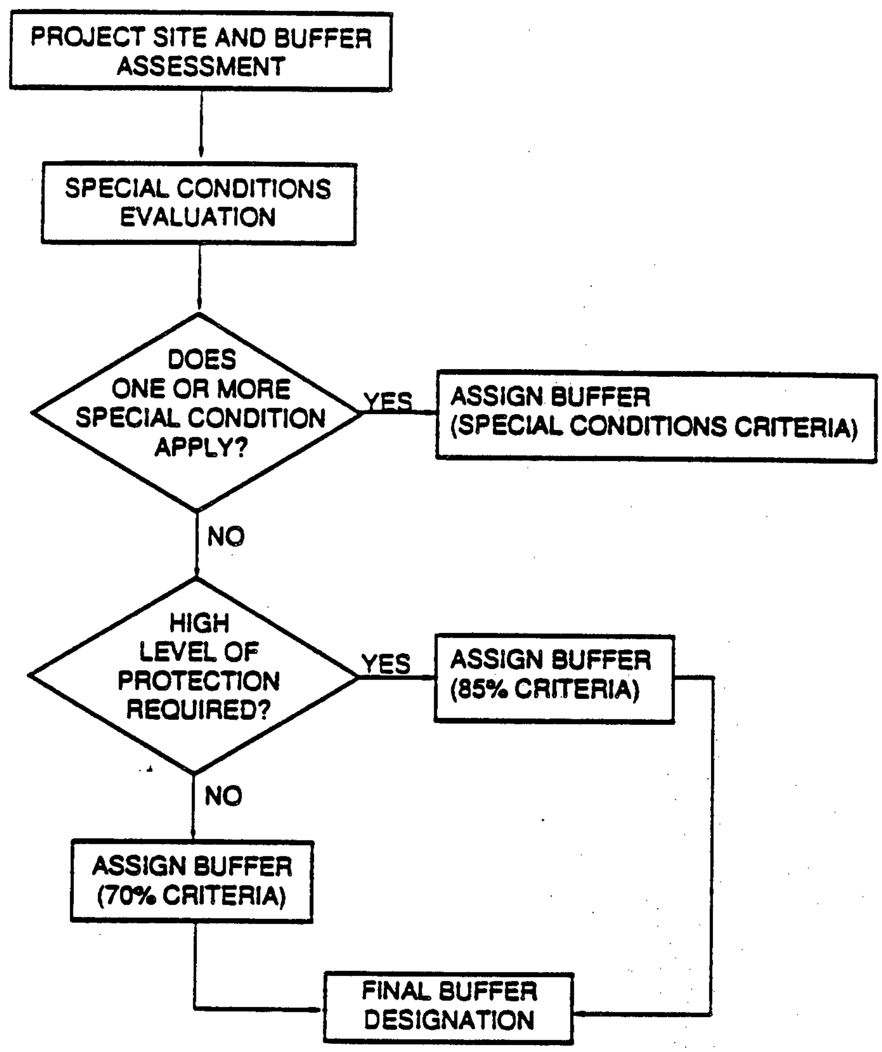
An outline of the draft IEP buffer determination model is presented in Figure 7. The initial assessment step involves gathering information about existing resources at the project area, including soil infiltration rates within the buffer. The second step recommends specific actions if a variety of special conditions apply at the site. Special conditions and recommended actions are summarized below:

Table 7: Example of Buffer Strip Matrix.*

Stream Class	Stream Order	Buffer Width (distance in feet), Slope (percent) <30	>30	>40	>50
Meadow	-	100	150	200	250
I	4+	100	150	200	250
II	3-4	100	100	150	200
III	2-3	50	100	100	150
IV	1-2	≤50	≤50	75	100
V	1-0	<50	<50	<50	<50

*: adapted from U.S. Forest Service (see CCDER, 1989 b).

Figure 7: IEP Buffer Determination Model



Adapted from IEP (1989)

Special Condition	Suggested Action
Proposed facility will have hazardous materials on site	Minimum 91 m (300 ft) buffer
Proposed facility will be in developed residential area	Buffer consistent with existing buffers
Potential buffer area with > 15 percent slope or < 80 percent vegetative cover	Other mitigative actions required since buffer is not suitable for water quality protection
Adjacent wetland provides potential habitat for threatened or endangered species	Consult state Natural Heritage Program

If no special conditions apply, buffer width is determined using the sediment retention model previously described on pages 9 and 11. In this study, for sensitive sites (i.e water supply reservoirs, coastal ponds), buffers were designed to remove 85 percent of total suspended sediments (as recommended by the Rhode Island Department of Environmental Management). For other sites, RI DEM recommends 70 percent removal of total suspended sediments.

The Cook College Dept. of Environmental Resources (CCDER, 1989 a,b) developed a watershed management model for protection of surface water quality from non point contamination in New Jersey. The model includes a methodology for determining buffer strip width to protect various types of surface waters. Buffer widths required to protect water quality are calculated using the sediment retention model described on page 12. Specific buffer strip width recommendations are then made as follows:

1) For perennial streams and lakes a 15 m (50 ft) minimum buffer or a buffer as determined by the sediment retention model (whichever is greater).

2) For non-terminal water supply reservoirs and water supply intakes a 50 m (100 ft) minimum buffer or buffer as determined by the sediment retention model (whichever is greater).

3) For terminal water supply reservoirs and water supply intakes a 91 m (300 ft) minimum buffer or buffer as determined by the sediment retention model (whichever is greater).

In all cases, areas within the buffer with slopes in excess of 15 percent or impervious surfaces are not credited as part of the required buffer width (see Figure 4).

The CCDER watershed management plan also suggested establishment of a "Special Restrictions Zone" upslope of the buffer. Activities within this zone with potential to generate non-point contaminants would be subject to special land use regulations.

The U.S. Forest Service is developing standards for the design, operation, and maintenance of forested riparian buffers strips to protect water quality in the eastern United States (Welsch, pers. commun.). Under the draft standards, riparian buffers would consist of three distinct zones.

Zone I would extend 4.5 m (15 ft) from the streambank. This zone is intended to provide a stable riparian ecosystem adjacent to the water's edge, remove nutrients, provide shade to control water temperature, and contribute detritus to the stream ecosystem. Water filtered by this zone would be limited to sheet flow or subsurface flow. Concentrated surface flows would be converted to sheet or subsurface flows prior to entering the zone. Only activities necessary to stabilize the buffer (i.e. selective logging of problem trees) or stream crossings would be permitted within this zone.

Zone II would begin at the edge of Zone 1 and occupy an additional strip of land with a minimum width of 18 m (60 ft). This zone would be expanded, as required, to include soils subject to frequent flooding or inundation (soil Hydrologic Groups C and D). Zone 2 would provide additional contact time for buffering processes to take place and provide for long term sequestering of nutrients in biomass. Water filtered by this zone would also be limited to sheet flow or subsurface flow. Concentrated flows would be converted to sheet flow or sub-surface flows prior to entering the zone. Ideally, zone II would also be forested. Vegetation would be periodically harvested to maintain vigorous growth and to remove sequestered nutrients and pollutants. Livestock would be excluded except for necessary stream crossings.

Zone III would provide space for any water control structures needed to convert concentrated flow to uniform sheet flow, prior to entering Zone II. Zone III would be wide enough only to serve its intended purpose, and would not be required in all instances. Vegetation would consist of grasses and forbs which would stabilize structures and filter sediments. Mowing and removal of clippings would be permitted to remove sequestered nutrients. Controlled grazing would be permitted, as long as it did not threaten the integrity of water control structures.

For streamside riparian buffers, the draft standards also recommend that the total buffer area should be at least one-third of the upland source area. For ponds and lakes, buffer strip area should be at least one-fifth the area of cropland and pastures in the source area.

SUMMARY AND CONCLUSIONS

The available literature suggests that fairly narrow buffer strips (i.e $\leq$ 30 m) adequately provide many riparian functions (see Table 8). Shade provided by trees in narrow (10-20 m wide) buffers is usually adequate to control the temperature of small streams. Under most circumstances 20 to 30 m wide buffers appear adequate to remove suspended sediments from surface flows, unless flows within buffers are channelized. Although narrow buffers may significantly reduce nitrogen levels in surface runoff and groundwater, there is insufficient information available to evaluate the ability of riparian buffer strips to retain phosphorus. Relatively wide buffers are probably required to provide sufficient habitat for riparian wildlife and plants, and to function as corridors linking larger "islands" of riparian habitat.

Although fixed buffer widths are sometimes suggested in the literature, appropriate buffer widths vary on a case by case basis with site topography, existing riparian zone development, water quality protection goals, and regional planning objectives. Several recently developed approaches for determining buffer strip width on a case by case basis were presented.

There appears to be insufficient information available in the literature to formulate a matrix to adequately relate needed buffer strip width to stream characteristics, upland land use, and riparian functions. Although this approach might be useful from a regulatory standpoint, most values in the matrix would reflect professional judgment, rather than sound data provided in the literature.

TABLE 8: Effectiveness of Riparian Buffer Strips.

Functional Value	Buffer Width (m)	Effective? (yes or no)	Location	Watershed Type	Reference
Stream Temperature Control	10	Yes	NH	Forested	1
	10-20	Yes	WV	Forested	2
	12	Yes	NC	Forested	3
	31	Yes	PA	Forested	4
	9	Yes	OR	Forested	5
	30	Yes	Aust.	Forested	6
	7*	No	GA	Forested	7
Sediment Retention					
	15-45	Yes	NH	Forested	8
	10-20	Yes	VW	Forested	2
	30	Yes	Aust.	Forested	6
	19	Yes	MD	Agricultural	9
	30	No	OR	Forested	26
Nutrient Retention					
Nitrogen	19	Yes	MD	Agricultural	9
Nitrogen	16	Yes	NC	Agricultural	10
Nitrogen	16	Yes	PA	Agricultural	11
Nitrogen	31**	No	PA	Forested	4
Phosphorus	50	Yes(?)	MD	Agricultural	9
Nitrogen/Phosphorus	10-20	No	VW	Forested	2
Pesticide Retention					
Pyrethroids					
ground applied	15	Yes	Canada	Forested	12
aerial spray	100	Yes	Canada	Forested	12
Hexazinone	15	No	VW	Forested	13

*: buffer partially damaged by blowdown

**: buffer partially damaged by blowdown, stream also received runoff from an unbuffered intermittent stream

TABLE 8: continued

Functional Value	Buffer Width (m)	Effective? (yes or no)	Location	Watershed Type	Reference
Streambank Stability					
	15	Yes	NJ	Suburban	14
	30	Yes	CA	Forested	15
Stream Structure (snags)	20-30	Yes	AK	Forested	16
	31	Yes	OR	Forested	17
Protect. of Aquatic Life					
Invertebrates	30	Yes	CA	Forested	18
Invertebrates	8-9	No	ME/NH	Forested	19
Fish	30	Yes	OR	Forested	20
Wildlife Habitat					
Songbirds	200	Yes	IO	Agricultural	21
Songbirds	175	Yes	ME	Forested	22
Songbirds	62	Yes	VA	Forested	23
Small Mammals	9-20	Yes	OR	Forested	24
Squirrels	55	Yes	TX		25

References: 1) Burton and Likens, 1973; 2) Aubertin and Patric, 1974; 3) see Corbett et al., 1978; 4) Lynch and Corbett, 1990; 5) Brazier and Brown, 1973; 6) Hopmans et al., 1987; 7) Hewlet and Forson, 1982; 8) see Karr and Schlosser, 1977; 9) Peterjohn and Correll, 1984; 10) Jacobs and Gilliam, 1985; 11) Schnabel, 1986; 12) Nriagu and Lakshminarayana, 1989; 13) Lavey et al., 1989; 14) Whipple et al., 1981; 15) Erman, 1977; 16) Murphy and Koski, 1989; 17) see Budd et al., 1987; 18) Erman et al., 1980; 19) Noel et al., 1988; 20) see Newbold et al., 1988; 21) Stauffer and Best, 1980; 22) Hooper, pers. commun.; 23) see Howard and Allen, 1988; 24) Cross, 1985; 25) Dickerson and Huntley, 1987; 26) Moring, 1982.

BIBLIOGRAPHY

Adams, L.W., L.E. Dove, 1989. Wildlife Reserves and Corridors in the Urban Environment: A Guide to Ecological Landscape Planning and Resource Conservation. National Institute for Urban Wildlife. Columbia, MD.

Asmussen, L.E., A.W. White, E.W. Hauser, and J.M. Sheridan, 1977. Reduction of 2,4-D load in surface runoff down a grassed waterway. J. Environ. Quality. Vol. 6: 159-162.

Aubertin, G.M., and J.H. Patric, 1974. Water quality after clearcutting a small watershed in West Virginia. J. Environ. Quality. Vol. 3: 243-249.

Aucutt, T., 1988. Riparian management in Idaho. National Wetlands Newsletter. Mar-Apr. pp. 4-6.

Bacon, C.G., 1990. Riparian silviculture - active riparian management for multiple resources. In: "Forestry on the Frontier". Soc. of American Foresters. Bethesda, MD. pp. 99-102.

Barfield, B.J., E.W. Tollner, and J.C. Hayes, 1979. Filtration of sediment by simulated vegetation, I. steady-state flow with homogeneous sediment. Transactions of the ASAE. Vol. 22: 540-545.

Barton, D.R., and W.D. Taylor, 1985. Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario streams. North American Journal of Fisheries Management. Vol. 5: 364-378.

Benke, A.C., R.L. Henry, D.M. Gillespie, and R.J. Hunter, 1985. Importance of Snag Habitat for Animal Production in Southeastern Streams. Fisheries. Vol. 10: 8-13.

Beschta, R.L., 1978. Long-term patterns of sediment production following road construction and logging in the Oregon coast range. Water Res. Bull. Vol. 14: 1011-1016.

Beshchta, R.L., and W.S. Platts, 1986. Morphological Features of Small Streams: Significance and Function. Water Res. Bull. Vol. 22: 370-379.

Beshchta, R.L. et al., 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. In: "Streamside Management: Forestry and Fishery Interactions". E.O. Salo and T.W. Cundy (eds). U. of Washington. Institute of Forest Resources. Seattle, Washington. pp. 191-224.

Bingham, S.C., P.W. Westerman, and M.R. Overcash, 1980. Effect of grass buffer zone length in reducing the pollution from land application areas. Trans. American Society of Agricultural Engineers. pp. 330-342.

Bisson, P.A., 1987. Large woody debris in forested streams in the pacific northwest: past present and future. In: "Streamside Management: Forestry and Fishery Interactions". E.O. Salo and T.W. Cundy (eds). U. of Washington. Institute of Forest Resources. Seattle, Washington. pp. 143-190.

Brazier, J.R. and G.W. Brown, 1973. Buffer Strips for Stream Temperature Control. Res. Paper No. 15. Forest Research Laboratory, School of Forestry, Oregon State University, Corvallis, OR.

Briggs, R.D., W.B. Krohn, J.G. Trial, W.D. Ostrofsky, and D.B. Field, 1989. Forest and Wildlife Management in New England - What Can We Afford? CFRU Information Report 21.

Brinson, M.M., B.L. Swift, R.C. Plantico, and J.S. Barclay, 1981. Riparian Ecosystems: Their Ecology and Status. U.S. Fish and Wildlife Service, Biol. Ser. Prog. FWS/OBS-81/17, Washington, D.C.

Brown, G.W. and J.T. Krygier, 1970. Effects of Clear-Cutting on Stream Temperature. Water Res. Research. Vol. 6: 1133-1139.

Brown, M.T. et al., 1987. Buffer Zones for Water Wetlands, and Wildlife: A Final Report on the Evaluation of the Applicability of Upland Buffers for the wetlands of the Wekiva Basin. Prepared for the St. Johns River Water Management District by Center for Wetlands, University of Florida, Gainesville, FL.

Budd, W.W., P.L. Cohen, and P.R. Saunders, 1987. Stream corridor management in the pacific northwest: I. determination of stream-corridor widths. Environ. Management. Vol. 11: 587-597.

Bull, E.L., 1977. Specialized habitat requirements of birds: snag management, old growth, and riparian habitat. In: "Proceedings of the Workshop on Nongame Bird Habitat Management in the Coniferous Forests of the Western United States. USDA Forest Service Gen. Tech. Rep. PNW-64. pp. 74-82.

Burdick, D.M., D. Cushman, R. Hamilton, J.G. Gosselink, 1989. Fanunal changes and bottomland hardwood forest loss in the Texas watershed, Louisiana. Conser. Biology. Vol. 3: 282-289.

Burns, J.E., 1970. The Importance of Streamside Vegetation to Trout and Salmon in British Columbia. Vancouver Island Region, Fish and Wildlife Branch, Department of Recreation and Conservation, Nanaimo, B.C.

Burns J.W., 1972. Some effects of logging and associated road construction on northern California streams. Trans. American Fisheries Society. Vol. 101: 1-17.

Burton, T.M., and G.E. Likens, 1973. The effect of strip-cutting on stream temperatures in the Hubbard Brook experimental forest, New Hampshire. BioScience. Vol. 23: 433-435.

Chen, M., 1988. Pollution of ground water by nutrients and fecal coliforms from lakeshore septic tank systems. Water, Air, and Soil Pollution. Vol. 37: 407-417.

Clausen, J.C. and D.W. Meals, Jr., 1989. Water quality achievable with agricultural best management practices. Journal of Soil and Water Conservation. Nov-Dec. pp. 593-596.

Cohen, P.L., P.R. Saunders, F.R. Steiner and W.W. Budd, 1987. Stream corridor management in the pacific northwest: II. management strategies. Environ. Management. Vol. 11: 599-605.

Cook College Dept. of Environmental Resources, 1989a. Watershed Management Strategies for New Jersey. New Jersey Agric. Exper. Station Report No. H-17505-1-89. New Brunswick, New Jersey.

Cook College Dept. of Environmental Resources, 1989b. Buffer Strips to Protect Water Supply Reservoirs and Surface Water Intakes: A model and Recommendations. New Jersey Agric. Exper. Station Report No. H-17505-2-89. New Brunswick, New Jersey.

Cooper, J.R., J.W. Gilliam, and T.C. Jacobs, 1986. Riparian areas as a control of nonpoint pollutants. In: "Watershed Research Perspectives". D.C. Correll (ed.). Smithsonian Institution Press. Washington, D.C. pp. 166-190.

Corbett, E.S., J.A. Lynch and W.E. Sopper, 1978. Timber harvesting practices and water quality in the eastern United States. Journal of Forestry. Vol: 484-485.

Correll, D.L. and W.T. Peterjohn, 1984. Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. Ecology. Vol. 65: 1466-1475.

Cromack, K., F.J. Swanson and C.C. Grier, 1979. A comparison of harvesting methods and their impact on soils and environment in the pacific northwest. In:"Forest Soils and Land Use". Proc. 5th North American Forest Soils Conference. pp. 449-476.

Cross, S.P., 1985. Responses of small mammals to forest riparian perturbations. In" Riparian Ecosystems and their Management: Reconciling Conflicting Uses". USDA Forest Service Gen. Tech. Rep. RM-120. pp. 269-275.

Cummins, K.W., M.A. Wilzbach, D.M. Gates, J.B. Perry, and W. B. Taliaferro, 1989. Shredders and riparian vegetation. BioScience. Vol. 39: 24-30.

Dennis, J., 1986. Phosphorus export from a low-density residential watershed and an adjacent forested watershed. In: "Lake and Reservoir Management" Vol. 2: 401-404.

Dickey, E.C. and D. H. Vanderholm, 1981. Vegetative filter treatment of livestock feedlot runoff. J. Environ. Quality. Vol. 10: 279-284.

Dickson, J.G., and J.C. Huntley, 1987. Riparian zones and wildlife in southern forests: the problem and squirrel relationships. In: "Managing Southern Forests for Wildlife and Fish". J.G. Dickson and O.E. Maughan (eds.). USDA Forest Service Gem Tech. Rep. SO-65. pp. 37-39.

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, V.O. Shanholtz, and W.L. Magette, 1986. Evaluating Nutrient and Sediment Losses from Agricultural Lands: Vegetative and Filter Strips. U.S. EPA. Annopolis, MD.

Dillaha, T.A., J.H. Sherrard, and D. Lee, 1986. Long-Term Effectiveness and Maintenance of Vegetative Filter Strips. Virginia Water Res. Res. Centr. Bull. No. 153. Blaksburg, VA.

Dillaha, T.A., J.H. Sherrard, D. Lee, S. Mostaghimi, and V.O. Shanholtz, 1988. Evaluation of vegetative filter strips as a best management practice for feed lots. Journal WPCF. Vol. 60: 1231-1238.

Doyle, A.T., 1990. Use of riparian and upland habitats by small mammals. J. Mammology. 71: 14-23.

Edwards, W.M, L.B. Owens, and R.K. White, 1983. Managing runoff from a small, paved beef feedlot. J. Environ. Qual. Vol. 12: 281-286.

Erman, D.C., E.D. Andrews, and M. Yoder-Williams, 1988. Effects of winter floods on fishes in the Sierra Nevada. Can. J. Fish. Aquatic Science, Vol. 45: 2195-2200.

Erman, D.C., and D. Mahoney, 1983. Recovery After Logging in Streams With and Without Bufferstrips in Northern California. California Water Resources Center, University of California, Davis, CA.

Erman, D.C., J.D. Newbold, and K.B. Roby, 1977. Evaluation of Streamside Buffer Strips for Protecting Aquatic Organisms. California Water Resources Center, University of California, Davis, CA, pp. 1-50.

E.P.A., 1976. Forest Harvest, Residue Treatment, Reforestation & Protection of Water Quality. EPA 910/9-76-020.

Fail, J.L., M.N. Hamzah, B.L. Haines, and R.L. Todd., 1986. Above and belowground biomass, production, and element accumulation in riparian forests of an agricultural watershed. In:"Water Research Perspectives". D.L. Correll (ed.). Smithsonian Institution Press. Washington, D.C. pp. 193-223.

Feller, M.C., 1981. Effects of clearcutting and slashburning on stream temperature in southwestern British Columbia. Water Res. Bull. Vol. 17: 863-867.

Fitzpatrick, C., 1986. The use of buffer strips in controlling agricultural runoff. In: "Stream Protection: the Management of Rivers for Instream Uses". I.C. Cambell (ed.). Water Studies Center. East Caulfield, Australia. pp. 75-84.

Forman, R.T, and M. Godron., 1986. Landscape Ecology. Wiley.

Forman, R.T.T., 1983. Corridors in a landscape: their ecological structure and function. Ekologia. Vol. 2: 375-387.

Foster, D.R., 1988. Species and Stand Response to Catastrophic Wind in Central New England, U.S.A. Journal of Ecology. Vol. 76: 135-151.

Gaines, D., 1974. A New Look at the Nesting Riparian Avifauna of the Sacramento Valley, California. Western Birds. Vol. 5: 60-81.

Ganem, B.V., 1989. Greenways - how wide? Rep. Prep. for Nashua River Watershed Association. Fitchburg, MA.

Garmen, G.C., and J.R. Moring, 1984. Initial Effects of Deforestation on Community Structure and Function of the East Branch Piscataquis River, ME. Thesis. University of Maine, Orono, ME.

Gilliam, J.W., and R.W. Skaggs, 1987. Natural buffer areas and drainage control to remove pollutants from agricultural drainage water. In: "Proceedings of the National Wetland Symposium: Mitigation of Impacts and Losses". J.A. Kusler et al. (eds.). Association of State Wetland Managers. Berne, NY. pp. 145-148.

Glinski, R.L., 1977. Regeneration and distribution of sycamore and cottonwood trees along Sonoita Creek, Santa Cruz County, Arizona. In: "Importance, Preservation and Management of Riparian Habitat: A Symposium". USDA Forest Service Gen. Tech. Rep. RM-43. pp. 116-123.

Gosselink, J.G., et al., 1990. Landscape Conservation in a Forested Wetland Watershed. BioScience. Vol. 40: 588-600.

Graynoth, E., 1979. Effects of logging on stream environment and faunas in Nelson. New Zealand Journal of Marine & Freshwater Research. Vol. 13: 79-109.

Hall, J.D., G.W. Brown, and R.L. Lantz, 1987. The Alsea Watershed Study: A Retrospective. In: "Streamside Management: Forestry and Fishery Interactions". E.O. Salo and T.W. Cundy (eds). U. of Washington. Institute of Forest Resources. Seattle, Washington. pp. 399-416.

Hanson, J.S., G.P. Malanson, and M.P. Armstrong, 1990. Landscape fragmentation and dispersal in a model of riparian forest dynamics. Ecological Modelling. Vol. 49: 277-296.

Harris, L.D., 1989. The faunal significance of fragmentation of southeastern bottomland forests. In: "The Forested Wetlands of the Southern United States". D.D. Hook and R. Lea (eds.). USDA Forest Service Gen. Tech. Report SE-50. pp 126-134.

Hartung, R.E., and S.W. Kress, 1977. Woodlands of the Northeast. USDA Soil Conservation Service and Forest Service.

Haupt, H.F., and W.J. Kidd, 1965. Good logging practices reduce sedimentation in central Idaho. J. Forestry. 63: 664-670.

Hayes J.C., B.J. Barfield, and R.I. Barnhisel, 1979. Filtration of sediment by simulated vegetation II. unsteady flow with non-homogeneous sediment. Trans. of the ASAE. Vol. 22: 1063-1067.

Hayes, J.C., B.J. Barfield, and R.I. Barnhisel, 1979. Performance of grass filters under laboratory and field Conditions. ASAE Paper No. 79-2530. ASAE, St. Joseph, MI.

Hayes, J.C. and J.E. Hairston, 1983. Modeling the long-term effectiveness of vegetative filters on on-site sediment controls. ASAE Paper No. 83-2081. ASAE St. Joseph, MI.

Heede, B.H., M.D. Harvey, and J.R. Laird, 1988. Sediment delivery linkages in a chaparral watershed following a wildfire. Environmental Management. Vol. 12: 349-358.

Heifetz, J., M.L. Murphy, and K.V. Koski, 1986. Effects of logging on winter habitat of juvenile salmonids in Alaskan streams. North Amer. J. of Fisheries Management. Vol. 6: 52-58.

Hewlett, J.D., and J.C. Fortson, 1982. Stream temperature under an inadequate buffer strip in the southeast peidmont. Water Res. Bull. Vol. 18: 983-988.

Hightshoe, G., 1978. Native Trees for Urban and Rural America. Iowa State Univer. Res. Found. Ames, IO.

Holler, S.M, 1989. Buffer Strips in Watershed Management. In: "Watershed Management Strategies for New Jersey". Cook College Dept. of Environmental Resources. New Jersey Agric. Exper. Stat. Report No. H-17505-1-89. New Brunswick, New Jersey. pp. 69-116.

Holtby, L.B., 1988. Effects of logging on stream temperatures in Carnation Creek, British Columbia, and associated impacts on the coho salmon. Can. J. Fish. Aquat. Science. Vol. 45: 502-515.

Hooper, S.T., 1989. Wildlife and Riparian Zones in Maine: A Review. In: "Forest and Wildlife Management in New England - What Can We Afford?" R.D. Briggs et al. (eds.). Misc. Rep. No. 336. Soc. Amer. Foresters. pp. 171-176.

Hopper, S.T., 1990. Personal. Communication. University of Maine, Orono, ME.

Hopmans, P., D.W. Flinn, and P.W. Farrell, 1987. Nutrient dynamics of forested catchments in southeastern Australia and changes in water quality and nutrient exports following clearing. Forest Ecology and Management. Vol. 20: 209-231.

Hornbeck, James W. and Kropelin, William, 1982. Nutrient removal and leaching from a whole-tree harvest of northern hardwoods. J. of Environ. Quality, Vol. 11:

Howard, R.J. and J.A. Allen, 1989. Streamside habitats in southern forested wetlands: their role and implications for managment. In: "The Forested Wetlands of the Southern United States". D.D. Hook and R. Lea (eds.). USDA Forest Service Gen. Tech. Report SE-50. pp 97-106.

Ice, G.C., 1990. Guidelines and approaches for forest riparian management: state forest practice rules. In: "Forestry on the Frontier". Soc. of American Foresters. Bethesda, MD. pp. 94-96.

IEP, Inc., 1990. Vegetated Buffer Strip Designation Method Guidance Manual (draft prepared for Narragansett Bay project). Northborough, MA.

Irland, L.C., 1985. Logging and water quality: state regulation in New England. J. Soil and Water Conser. Jan-Feb. pp. 98-102.

Jacobs, T.C. and Gilliam, J.W., 1983. Nitrate Loss From Agricultural Drainage Waters: Implications For Nonpoint Source Control. Department of Soil Science, North Carolina State University, Raleigh, NC. UNC-WRRI-83-209.

Jacobs, T.C. and Gilliam, J.W., 1985a. Riparian losses of nitrate from agricultural drainage waters. J. of Environ. Qual. Vol. 14: 472-478.

Jacobs, T.C. and Gilliam, J.W., 1985b. Headwater stream losses of nitrogen from two coastal plain watersheds. J. of Environ. Qual. Vol. 14: 467-471.

Hanson, R.R., L.T. Haight, and J.M. Simpson, 1977. Endangered species vs. Endangered habitats: a concept. In: "Importance, Preservation and Management of Riparian Habitat: A Symposium". USDA Forest Service Gen. Tech. Rep. RM-43. pp. 68-79.

Johnson, S.W., J. Heifetz, and K.V. Koski, 1986. Effects of Logging on the Abundance and Seasonal Distribution of Juvenile Steelhead in Some Southeastern Alaska Streams. North American J. of Fisheries Management. Vol. 6: 532-537.

Jones, J.J., J.P. Lortie, and U.D. Pierce, Jr., 1988. The Identification and Management of Significant Fish and Wildlife Resources in Southern Coastal Maine. Maine Department of Inland Fish and Wildlife, Augusta, ME.

Jordan, R.A. and J.K. Shisler, 1988. Research needs for the use of buffer zones for wetland protection. In:"Proceedings of the National Wetland Symposium: Mitigation of Impacts and Losses" Assoc. State Wetland Managers. Berne, NY. pp. 433-435.

Jordan, T.E., D.L. Correll, W.T. Peterjohn, and D.E. Weller, 1986. Nutrient flux in a landscape: the Rhode River watershed and receiving waters. In: "Watershed Research Perspectives". Smithsonian Institute Press. Washington, D.C. pp. 57-75.
Krohn, W.B. 1990. Personal Communication. Maine Coop. Fish. Wildlife Unit. Orono, ME.

Karr, J.R. and I.J. Schlosser, 1977. Impact of Nearstream Vegetation and Stream Morphology on Water Quality and Stream Biota. U.S. EPA. 600/3-77-097.

Karr, J.R. and I.J. Schlosser, 1978. Water resources and the land-water interface. Science. Vol. 201: 229-234.

Knoff, F.L., R. Johnson, T. Rich, F.B. Samson, and R.C. Szaro, 1988. Conservation of riparian ecosystems in the United states. Wilson Bull. vol 100: 272-284.

Kuenzler, E.J., 1989. Value of forested wetlands as filters for sediments and nutrients. In: "The Forested Wetlands of the Southern United States". D.D. Hook and R. Lea (eds.). U.S. Forest Service Gen. Tech. Report SE-50. pp 85-96.

Kunkle, S.H., 1970. Sources and Transport of Bacterial Indicators in Rural Streams. In: "Proceedings of Symposium on Interdisciplinary Aspects of Watershed Management." American Society of Civil Engineers. pp. 105-132.

Kwak, T.J., 1988. Lateral Movement and Use of Floodplain Habitat by Fishes of the Kankakee River, Illinois. American Midland Naturalist. Vol. 120: 241-249.

Lavy, T.L., J.D. Mattice, and J.N. Kochenderfer, 1989. Hexazinone persistence and mobility of a steep forested watershed. J. Environment Quality. Vol. 18: 507-514.

Leedy, D.L., R.M. Maestro, and T.M. Franklin, 1978. Planning for Wildlife in Cities and Suburbs. Urban Wildlife Research Center, Inc. Ellicott City, MD.

Lenat, D.R., 1984. Agricultural and stream water quality: a biological evaluation of erosion control practices. Environmental Management. Vol. 8: 333-344.

Lenat, D.R., 1984. Agricultural runoff and erosion control practices. Environmental Management. Vol. 8: 333-343.

Lines, L.G., and L.D. Harris, 1989. Isolation of nature reserves in north Florida: measuring linkage exposure. Trans. 54th N. A. Wildlife & Natural Resources Conference. pp. 113-120.

Lowney, M.S., and E.P. Hill, 1988. Wood duck nest sites in bottomland hardwood forest of Mississippi. J. Wildlife Management. Vol. 53: 378-382.

Lowrance, R. and R.A. Leonard, 1988. Streamflow nutrient dynamics on coastal plain watersheds. J. Environ. Quality. Vol. 17: 734-740.

Lowrance, R.R., R. Leonard, and J. Sheridan, 1985. Managing riparian ecosystems to control nonpoint pollution. J. Soil and Water Conser. Jan-Feb. Vol. 40: 87-91.

Lowrance, R. R., S. McIntyre, and C. Lance, 1988. Erosion and deposition in a field/forest system estimated using cesium-137 activity. J. Soil and Water Conserv. March-April

Lowrance, R., J.K Sharpe, and J.M. Sheridan, 1986. Long-term sediment deposition in the riparian zone of a coastal plain watershed. J. Soil and Water Conser. Jul-Aug. pp. 266-271.

Lowrance, R.R., R.L. Todd, and L.E. Asmussen, 1983. Waterborne nutrient budgets for the riparian zone of an agricultural watershed. Agric. Ecosystems and Environment. Vol. 10: 371-384.

Lowrance, R., R.L. Todd, and L.E. Asmussen, 1984a. Nutrient cycling in an agricultural watershed: I. phreatic movement. J. Environ. Quality. Vol. 13: 22-26.

Lowrance, R. R., R.L. Todd, and L.E. Asmussen, 1984b. Nutrient cycling in an agricultural watershed: II. streamflow and artifical drainage. J. Environ. Quality. Vol. 13: 27-32.

Lowrance, R.R., et al., 1984. Riparian forests as nutrient filters in agricultural watershed. BioScience. Vol. 34: 374-377.

Lynch, J.A., and E.S. Corbett, 1990. Evaluation of best management practices for controlling nonpoint pollution from silvicultural operations. Water Res. Bull. Vol. 26: 41-52.

MacClintock, L., B.L. Whitcomb, and R.F. Whitcomb, 1977. Evidence for the values of corridors and minimization of isolation in preservation of biotic diversity. American Birds. Vol. 31: 6-12.

Manci, K.M., 1989. Riparian Ecosystem Creation and Restoration: A Literature Summary. U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C.. Biological Report 89(20).

Margules, C.R., A.O. Nicholls, and R.L. Pressey, 1988. Selecting networks of reserves to maximize biological diversity. Biological Conservation. Vol. 43: 63-76.

Marsh, P.C., and J.E. Luey, 1982. Oases for aquatic life within agricultural watersheds. Fisheries. Vol. 7: 16-19.

Martin, C.W., D.S. Noel, and C.A. Federer, 1984. Effects of forest clearcutting in New England stream chemistry. J. Environ. Quality. Vol. 13: 204-210.

Martin, C.W., and R.S. Pierce, 1980. Clearcutting patterns affect nitrate and calcium in streams of New Hampshire. Journal of Forestry. Vol. 88: 268-272.

Martin, D.C. and W. Van Winkle, Jr., 1973. A home range model for animals inhabiting an ecotone. Ecology. Vol. 54: 205-209.

McGarigal, K., and W.C. McComb, 1989. Riparian wildlife information needs in western Oregon: land manager concerns. Trans. 54th Northern America Wildlife & Natural Resources Conference. pp. 32-41.

Meehan, W.R., F.J. Swanson, and J.R. Sedell, 1977. Influences of riparian vegetation on aquatic ecosystems with particular reference to salmonid fishes and their food supply. In: "Importance, Preservation and Management of Riparian Habitat: A Symposium". USDA Forest Service Gen. Tech. Rep. RM-43. pp. 137-145.

Megahan, W.F., 1980. Nonpoint source pollution from forestry activities in the western United States: results of recent research and research needs. In: "Proceedings of Forestry and Water Quality: What Course in the 80's? An Analysis of Environmental and Economic Issues". Water Pollution Control Federation, Washington, D.C. pp. 19-20.

Minshall, G.W., et al., 1985. Developments in Stream Ecosystem Theory. Can. J. Fish. Aquatic Science. Vol. 42: 1045-1054.

Mitsch, W.J. and J.G. Gosselink, 1986. Wetlands. Van Nostrand Reinhold.

Moring, J.R., 1982. Decrease in stream gravel permeability after clear-cut logging: an indication of intragravel conditions for developing salmonid eggs and alevins. Hydrobiologia: Vol 88: 295-298.

Motrini, R., 1980. The Importance of Riparian Zones to Terrestrial Wildlife. U.S. Fish and Wildlife Service. Sacramento, CA.

Murphy, M.L., J. Heifetz, S.W. Johnson, K.V. Koski, and J.F. Thedinga, 1986. Effects of clear-cut Logging with and without buffer strips on juvenile salmonids in Alaskan streams. Can. J. Fish. Aquatic Science. Vol. 43: 1521-1533.

Murphy, M.L., and K.V. Koski, 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North American J. Fisheries Management. Vol. 9: 427-436.

Neibling, W.H. and E.E. Alberts, 1979. Composition and yield of soilparticles transported through sod strips. ASAE Paper No. 79-2065. ASAE. St. Joseph, MI.

Newbold, J.D., D.C. Erman, and K.B. Roby, 1980. Effects on logging on macroinvertebrates in streams with and without buffer strips. Can. J. Fish. Aquatic Science. Vol. 37: 1076-1085.

New Jersey Dept. Environmental Protection, 1989. Evaluation and Recommendations Concerning Buffer Zones Around Public Water Supply Reservoirs.

New Jersey Dept. of Environmental Protection. 1983. Technical Basis for 25-foot-wide and 50-foot-wide Buffer Strips. Trenton, NJ.

New York Depart. of Environmental Conservation. 1986. Stream Corridor Management: A Basic Reference Manual. Albany, NY.

Nilsson, C., G. Grelsson, M. Johansson, and U. Sperens, 1988. Can rarity and diversity be predicted in vegetation along river banks? Biological Conservation. Vol. 44: 201-212.

Nilsson, C., G. Grelsson, M. Johnansson, and U. Sperens, 1989. Patterns of plant species richness along riverbanks. Ecology. Vol. 70: 77-84.

Noel, D.S., C.W. Martin, and C.A. Federer, 1986. Effects of forest clearcutting in New England on stream macroinvertebrates and periphyton. Environmental Management. Vol. 10: 661-670.

Noss, R.F., 1983. A regional landscape approach to maintain diversity. BioScience. Vol. 33: 700-706.

Noss, R.F., 1987. Corridors in real landscapes: a reply to Simberloff and Cox. Conservation Biology. Vol. 1: 159-164.

Noss, R.F., and L.D. Harris, 1986. Nodes, networks, and MUMs: preserving diversity at all scales. Environmental Management. Vol. 10: 299-309.

Nriagu, J.O., and J.S.S. Lakshminarayana, 1989. Aquatic Toxicology and Water Quality Management. Wiley.

Omernik, J.M., 1977. Nonpoint Source-Stream Nutrient Level Relationships: A Nationwide Study. Corvallis Environmental Research Laboratory, Corvallis, Oregon. EPA-600/3-77-105.

Omernik, J.M., A.R. Abernathy, and L.M. Male, 1981. Stream nutrient levels and proximity of agricultural and forest land to streams: some relationships. J. Soil Water. Conserv. 36: 227-231.

Peterjohn, W.T., and D.L. Correll, 1984. Nutrient dynamics in an agricultural watershed: observations of the role of riparian forest. Ecology. Vol. 65: 1466-1475.

Peterjohn, W.T., and D.L. Correll, 1986. The effect of riparian forest on the volume and chemical composition of baseflow in an agricultural watershed. In:"Watershed Research Perspectives." D.L. Correll (ed.). Smithsonian Institute Press. Washington, D.C. pp. 244-258.

Peterson, R.C., et al., 1987. Stream management: emerging global similarities. Ambio. vol 16. 166-179.

Platts, W.S., J.N. Rinne, 1985. Riparian and stream enhancement management and research in the rocky mountains. North American J. of Fisheries Management. Vol. 5, 115-125.

Platts, W.S., et al., 1987. Methods for Evaluating Riparian Habitats With Applications to Management. USDA Forest Service Gen Tech. Rep. Int-221.

Peverly, J.H., 1982. Stream transport of nutrients through a wetland. J. Environ. Quality. Vol. 11: 38-43.

Radz, D. and R. Hovey, 1983. Steam Temperature Prediction Model. New York State Depart of Environmental Conservation, Bureau of Water Resources. Albany, NY.

Ranney, J.W., M.C. Bruner, and J.B. Levenson, 1981. The importance of edge in the structure and dynamics of forest islands. In: "Forest Island Dynamics in Man-Dominated Landscapes". R.L. Burgess and D.M. Sharpe (eds.). Springer-Verlag. pp. 67-95.

Reese, K.P., and J.T. Ratti, 1988. Edge effect: a concept under scrutiny. Trans. 53rd N.A. Wildl. & Nat. Res. Conf. pp. 127-136.

Rinne, J.N., 1988. Grazing effects on stream habitat and fishes: research design considerations. North American J. Fisheries Management. Vol. 8: 240-247.

Robinson, S.K., 1988. Reappraisal of the costs and benefits of habitat heterogenity for nongame wildlife. Trans. 53rd N. A. Wildl. & Nat. Res. Conf. pp. 145-155.

Rogers, Golden, and Halpern, Inc. 1988. New Jersey Freshwater Wetlands Protection Act as it Relates to Stream Corridor Buffer Considerations in the State Development and Redevelopment Plan. Philadelphia, PA. (prep. for N.J. Office of State Planning).

Rohde, W.A., L.E. Asmussen, E.W. Hauser, R.D. Wauchope, and H.D. Allison, 1980. Trifluralin movement in runoff from a small agricultural watershed. J. Environ. Quality. Vol. 9: pp. 37-42.

Roman, C. and R. Good, 1985. Buffer Delineation Model for New Jersey Pinelands Wetlands. Division of Pinelands Research Center for Coastal and Environmental Studies. Rutgers, N.J.

Salo, E.O. and T.W. Cundy (eds), 1987. Streamside Management: Forestry and Fish Interactions. U. of Washington Institute of Forest Resources. Seattle, Washington. Contrib. No. 57.

Schlosser, I.J., and J.R. Karr, 1981a. Riparian vegetation and channel morphology impact on spatial patterns of water quality in agricultural watersheds. Environmental Management. Vol. 5: 223-243.

Schlosser, I.J., and J.R. Karr, 1981b. Water quality in agricultural watersheds: impact of riparian vegetation during base flow. Water Res. Bull. Vol. 17: 233-240.

Schnabel, R.R., 1986. Nitrate concentrations in a small stream as affected by chemical and hydrologic interactions in the riparian Zones. In: "Watershed Research Perspectives." D.L. Connell (ed.). Smithsonian Institute Press. Washington, D.C. pp. 263-281.

Schueler, T.R., 1987. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs. Metropolitan Washington Council of Governments.

Sedell, J.R., and J.L. Froggatt, 1984. Importance of streamside forests to large rivers: the isolation of the Willamette River, Oregon, U.S.A., from its floodplain by snagging and streamside forest removal. Verh. Internat. Verein. Limnol. Vol. 22: 1828-1834.

Schwer, C.B., and J.C. Clausen, 1989. Vegetative filter treatment of dairy milkhouse wastewater. J. Environ. Qual. Vol. 18: 446-451.

Sidle, R.C., 1989. Overview of Cumulative Effects Concepts and Issues. In: "Forestry on the Frontier". Soc. of American Foresters. Bethesda, MD. pp. 103-107.

Sidle, R.C., 1989. Cumulative effects of forest practices on erosion and sedimentation. In: "Forestry on the Frontier. Soc. of American Foresters. Bethesda, MD. pp. 108-112.

Simberloff, D., and J. Cox, 1987. Consequences and costs of conservation corridors. Conservation Biology. Vol. 1: 63-71.

Simpson, M.B., 1969. The prothonotary warbler in the Carolina Piedmont. Chat. vol. 33, pp. 31-37.

Small, M.F., and W.N. Johnson, Jr., 1986. Wildlife Management in Riparian Habitats. In:"Is Good Forestry Good Wildlife Management?" Maine Agric. Stat. Misc. Publ. No. 689. Orono, ME. pp. 69-79.

Stauffer, D.F. and L.B. Best, 1980. Habitat selection by birds of riparian communities: evaluating effects of habitat alterations. J. Wildlife Management. Vol. 44: 1-15.

Steinblums, I.J., H.A. Froehlich, and J.K. Lyons, 1984. Designing Stable Buffer Strips for Stream Protection. Journal of Forestry. Vol: 84: 49-52.

Sullivan, K., T.E. Lisle, C.A. Dolloff, G.E. Grant, L.M. Reid, 1987. Stream channels: the link between forests and fishes. In: "Streamside Management: Forestry and Fishery Interactions". E.O. Salo and T.W. Cundy (eds). U. of Washington. Institute of Forest Resources. Seattle, Washington. pp. 39-97.

Swift, B.L., 1984. Status of riparian ecosystems in the United States. Water Res. Bull. Vol 20: 223-228.

Thedinga, J.F., M.L. Murphy, J. Heifetz, K.V. Koski, and S.W. Johnson, 1989. Effects of logging on size and age composition of juvenile coho salmon (Oncorhynchus kisutch) and density of presmolts in southeast Alaska streams. Can. J. Fish. Aquatic Science. Vol. 46: 1383-1391.

Thomas, G.W., and J.D. Crutchfield, 1974. Nitrate-nitrogen and phosphorus contents of streams draining small agricultural watersheds in Kentucky. J. Environ. Quality. Vol. 3: 46-49.

Thompson, D.B., J.B. Gerrish, and T.L Loudon, 1979. Animal manure movement in winter runoff for different surface conditions. In: "Best Management Practices for Agriculture and Siliculture." R.C. Loehr et al. (eds.). Ann Arbor Sci. Pub. pp. 145-157.

Toumey, J.W., and C.F. Korstian, 1947. Foundations of Silviculture Upon an Ecological Basis. Wiley.

Trimble, G.R., 1959. Logging roads in northeastern municipal watersheds. J. Amer. Water Works Association. Vol. 51: 407-410.

Trimble, G.R. and R.S. Sartz, 1957. How far from a stream should a logging road be located? J. Forest. Vol. 55: 339-341.

Triska, F.J., 1984. Role of wood debris in modifying channel geomorpholohy and riparian areas of a large lowland river under pristine conditions: a historical case study. Verh. Internat. Verein. Limnol. Vol. 22: 1876-1892.

USDA Forest Service, 1979. The Importance of Riparian Habitats and Their Management to Wildlife and Fisheries. U.S. Forest Service Intermountain Region.

USDI Bureau of Land Management, 1979. USDI Bureau of Land Management Manual. Washington, D.C.

Wallace, J.B., and A.C. Benke, 1984. Quantification of wood habitat in subtropical coastal plain streams. Can. J. Fish. Aquatic Science. Vol. 41: 1643-1652.

Wauchope, R.D., 1978. The pesticide content of surface water drainage from agricultural fields - a review. J. of Environ. Quality. Vol. 7: 459-472.

Welsch, D., 1990. Personal Communication. U.S. Forest Service, Radnor, PA.

Wenger, K.F., 1984. Forestry Handbook. Wiley.

Wengrzynek, B., 1990. Personal Communication. Maine Soil Conservation Service. Fort Kent, ME.

Wesche, T.A., C.M. Goertler, and C.B. Frye, 1987. Contribution of riparian vegetation to trout cover in small streams. North American J. Fisheries Management. Vol. 7: 151-153.

Whigham, D.F., C. Chitterling, B.Palmer, and J. O'Neill, 1986. Modification of runoff from upland watersheds - the influence of a diverse riparian ecosystems. In: "Watershed Research Perspectives". D.L. Correll (ed.). Smithsonian Institution Press. Washington, D.C. pp. 305-331.

Whipple, W. Jr., J.M. DiLouie, and T. Pytalr, Jr., 1981. Erosional potential of streams in urbanizing areas. Water Res. Bull. Vol. 17: 36-45.

Williams, R.D. and A.D. Nicks, 1988. Using CREAMS to simulate filter strip effectiveness in erosion control. J. Soil and Water Conserv. Jan-Feb. pp. 108-112.

Wilson, B.N., B.J. Barfield, and R.W. Warner, 1986. Simple models to evaluate nonpoint pollution sources and controls. In: "Agricultural Nonpoint Pollution Sources and Controls". A. Giorgini and F. Zingales. (eds). Elsevier. pp. 231-263.

Wilzbach, M.A., 1986. Response of stream fish populations to changing land use. In: "Stream Protection: The Management of Rivers for Instream Uses". I.C. Campbell (ed.). Water studies Centre. Chisholm Inst. Tech. East Caulfield, Aust. pp. 85-94.

Winterbourn, M.J., 1986. Forestry practices and stream communities with particular reference to New Zealand. In: "Stream Protection: The Management of Rivers for Instream Uses". I.C. Campbell (ed.). Water studies Centre. Chisholm Inst. Tech. East Caulfield, Aust. pp. 57-73.

Wong, S.L. and R.H. McCuen, 1981. Design of Vegetative Buffer Strips for Runoff and Sediment Control (research paper). University of Maryland, Department of Civil Engineering. College Park, MD.

Woodall, S.L., 1985. Influence of Land Treatments on Temperature Variations of Groundwater Effluent to Streams. Thesis. University of Georgia. Athens, GA.

Young, R.A., T. Huntrods, and W. Anderson, 1980. Effectiveness of vegetated buffer strips in controlling pollution from feedlot runoff. J. Environ. Quality. Vol. 9: 483-487.

Zirschky, J., D. Crawford, L. Norton, and D. Deemer, 1989. Metal removal in overland flow. Journal WPCF. Vol. 16:470-475.